ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Master Thesis

FUELMAT GROUP

FUELING A SOFC WITH AGRICULTURAL WASTE DERIVED BIOGAS

- ANALYSING THE SWISS CASE -

Author:
Samuel Majerus

Supervisors:
Ing. Dirk Lauinger
Dr. Jan Van Herle

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Abstract

The use of fuel cells for valorising agricultural and food-waste-derived biogas in Switzerland is studied. The Swiss agricultural case is characterised by farms with small numbers of animals (20 cows) and high feed-in tariffs for biogas derived electricity. Thus, small-scale biogas installations are reviewed and the possibility to couple them with solid oxide fuel cells and photovoltaic panels is analysed. The average Swiss farm has a biogas potential of 63.6 MWh_{ch}, which can be converted with a 3.8 kW_{el} SOFC, producing 130% more electricity than a conventional small-scale engine. It is shown that solid oxide fuel cells become competitive over combustion engines if the investment cost of the first decreases to 13,000 CHF/kW_{el} with a lifetime of 10 years. However, a small-scale biogas installation is not profitable yet: the main challenge is to bring down the lifetime cost of the fuel cells and to reduce the investment cost of small-scale biogas facilities to around 6,000 CHF/kW_{ch}. The case of equipping the EPFL and UNIL sites with a digester and a solid oxide fuel cell is examined and is considered feasible from a technical and legal point. Each year 228 tons of food waste are collected and 3 tons of vegetable oil, which amount to fuel a SOFC in the range of 6.5 - 17.2 kW continuously on biogas, producing 50 - 150 MWh of electricity. Hence, the main challenge is not the conception of the plant, but the necessary permits and authorisations.

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I am sincerely thankful to my supervisor, Dr. Jan Van Herle, for his support and advice throughout this year as well as his enthusiasm about this project, which instantaneously was passed on to me. I would like to thank Dirk Lauinger for his help and guidance during this semester. I don't think it is possible to have a better assistant. Furthermore, I would like to thank all the people who took time to answer my questions, in particular Yves Membrez for receiving us, for the invitations to his conferences, and for all the additional help he gave me. I would also like to express my gratitude to Phillippe Vollichard, Aurore Nembrini and Prof. Christophe Hollinger from the EPFL for their interest in my project and for their advice. I would also like to thank Sylvain Boéchat, Nicolas de Arespacochage Sanitago, Veerle Devos-Delbecque and Laurence Tock for their help and specific answers. In addition, I would like to say thank you to Delphine Douçot and Christophe Dubois for the information on the collected food waste on campus. Thank you also to Dr. Clive Muller from the Canton the Vaud, to Matthieu Buchs from the OFEN, and to Johnny Fleury from the OFAG. I will also like to show gratitude to Odile Linden for reviewing my project. Also thank you to the whole FUELMAT group, it was always a pleasure to come to Sion. Another thank you to my family for their help and support. Finally, a big thank you to Andrea for taking care of me, supporting me, and for motivating me throughout this semester.

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Acronyms

AD	Anaerobic Digestion
CHP	Combined Heat and Power
C/N	Carbon to Nitrogen ratio
DFW	Digested Food Waste
DM	Dry Matter content
EPFL	Swiss Federal Institute of Technology Lausanne
FC	Fuel Cell
FCE	Fuel Converting Equipment
FW	Food Waste
FM	Fresh Matter
HHV	Higher Heating Value
ICE	Internal Combustion Engine
LEC	Levellised Electricity Cost
LHV	Lower Heating Value
NG	Natural Gas
MCFC	Molten Carbonate fuel cell
MT	Micro-Turbine
NPV	Net Present Value
PV	Photovoltaic Panels
SOFC	Solid Oxide Fuel Cell
TS	Total Solids content
UNIL	University of Lausanne
VS	Volatile Solids content
WWTP	Waste Water Treatment Plant

Notations

$CAPEX$	Captial Expenditure	CHF
$OMEX$	Operation andMaintenance Expenditure	CHF
LEC	Levellised Electricity Cost	CHF/kWh$_{el}$
$\tau_{\text{retention}}$	Retention Time	days
VS	VS in proportion of wet mass	%ofwetmass
E_{ch}	Chemical energy	kWh

Introduction

Over twenty years ago, the Intergovernmental Panel on Climate Change (IPCC) has presented strong evidence that man's actions influence the climate - mostly through the emission of greenhouse gases [2]. Even though several climate protocols, which aim at reducing greenhouse gas emissions, have been signed, the concentration of CO_2, the gas responsible for most of man-made climate change, in the atmosphere has been rising steadily (see Figure 1).

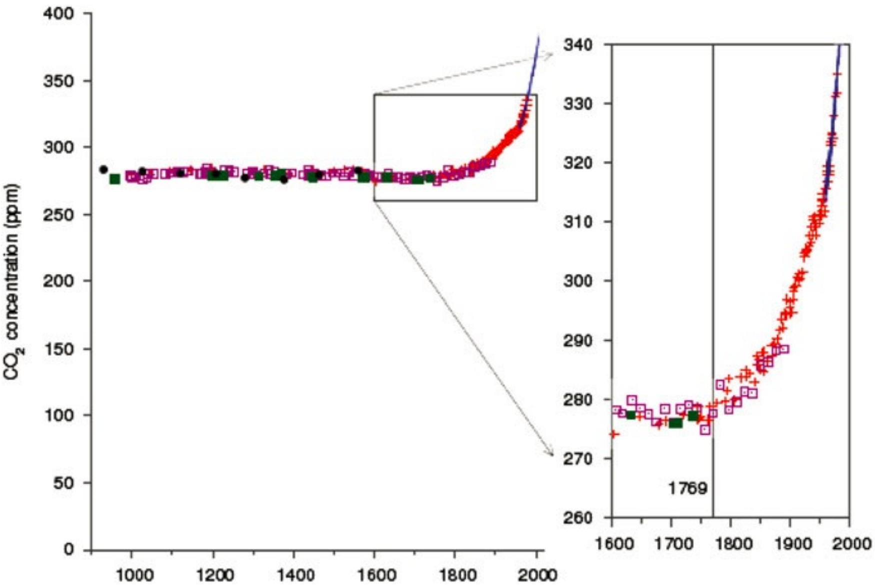


Figure 1: Variation in the CO_2 concentration since 950 [1]

During the 21st Conference of the Parties (COP) in Paris last year, the 195 member nations of the United Nations Framework Convention on Climate Change agreed to limit global warming to 1.5 °C as compared to pre-industrial levels [5]. Over the period from 1880 to 2012, the earth has already warmed by 0.85 °C [4]. In order to reduce emissions, many countries are rethinking their energy policy.

In the aftermath of the 2011 Fukushima nuclear disaster, the Swiss Federal Council has developed a long term energy policy called "Energy Strategy 2050" [7]. Although the primary goal is to become independent of nuclear energy, it also aims at reducing CO_2 emissions, reinforcing energy efficiency, and increasing the amount of renewable sources in the energy mix .

In Europe, the share of renewable energies in the gross electricity generation has more than doubled from 12.6% in 1990 to 27.2% in 2013 [9]. Most of the renewable electricity comes from hydro (45.4%), followed by wind (26.5%), biomass and waste (17.7%), solar (9.6%) and geothermal (0.7%) energy.

There is, however, still a strong dependency on fossil fuels. Natural gas (NG), a hydrocarbon gas mixture with methane as its main constituent, is a cleaner fuel than oil and coal. Nevertheless, its combustion causes air pollution and climate change. Natural gas represents 23% of the total primary energy in the European Union [10]. Almost eighty percent of the natural gas needs are imported - mainly from Russia (39.0%) and Norway (29.5%) [9], which shows how deficient European self-reliance is. This dependency on foreign gas can be a geopolitical weakness, as became apparent in the Russian-Ukraine conflict. Indeed, Russia stopped supplying gas to Ukraine in 2006, in the winter of 2008-09 and twice in 2015 [11]. Such hostilities could flare up again in future political discords and put Europe's reliance on foreign natural gas resources at stake.

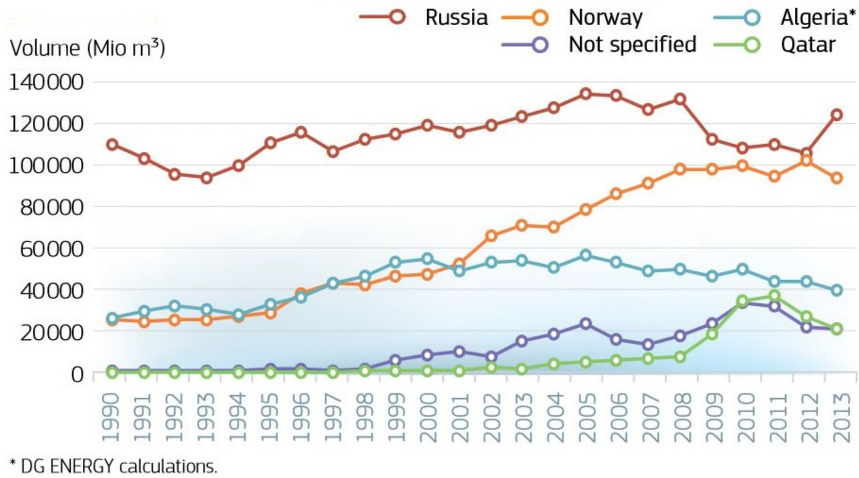


Figure 2: Top 5 Natural Gas Imports from Extra-EU Suppliers, [9]

Considering the drawbacks emanating from potential conflicts, not only on a political but also economic level, the advantages that self-reliance in providing our own resources of natural gas provides us with should be looked at. Indeed, domestically sourced biogas allows reducing gas imports and greenhouse gas emissions. Biogas is considered to be CO_2 neutral or negative, depending on which substrate is used. The CO_2 released during combustion is absorbed during the growth phase of the plants. When manure or food waste decomposes naturally, it emits methane, nitrous oxide, and ammonia, which have a higher warming potential than the CO_2 that is emitted through the combustion of the biogas [13]. In the United States solid waste of domesticated animals is responsible for more than a quarter of the methane emissions from agriculture [19], which a UN report found to be more harmful to the environment than the transportation industry by emitting more than 18% of the worldwide greenhouse gases [22] [1].

In areas such as Switzerland, where the arable land is limited, energy crops such as maize, cannot be deployed on a massive scale [31]. If this were the case, the biogas suppliers would compete with food production, a sector that already relies on subsidies for their subsistence [14]. These concerns do not apply to digesting waste products.

Biogas is the resulting gas mixture of the fermentation of organic waste in a digester. Coupling the digester with a cogeneration unit allows producing both heat and electricity. The heat can be used locally on the farm. As far as the digester is concerned, the electricity it generates is most commonly exported to the national grid and thus the farmer can profit from feed-in tariffs.

A recent report by the Federal Office of Energy found that biogas is a vastly underused resource in Switzerland [17], as only 4.7% of the agricultural potential is used, one reason being that Swiss farms tend to be small. Most biogas plants on the European market are in the 100 kW range. The average

[1]The report suggests that the methane emissions can be reduced *through improved diets to reduce enteric fermentation (digestive process), improved manure management and biogas production.*

Swiss farm, however, has about 20 cows, which corresponds to an electric potential of between 1 to 6 kW when equipped with a combustion engine. Installing 2 kW engines allows capturing 86% of the agricultural biogas potential (4,400 GWh per year) according to the same study. It is hard to find engines in this power range. Furthermore, the existing ones have a relatively low efficiency of around 25%.

Considering these findings, and especially the dramatic climate-changes that have occurred over the last decades, combined with the disastrous consequences for humanity, but also the economic and environmental repercussions that the on-going research into alternative resources of energy may have on our present lives, I have come to the conclusion to focus my research on the production of biogas and on its efficient conversion. Keeping in mind the vast potential of biogas and the low efficiency of engines, this study aims to analyse the use of fuel cells for the valorisation of biogas. At power levels in the kW range, fuel cells are about two times more efficient for the electrical conversion than engines.

After reviewing the principles of biogas (section 1.1) and fuel cells (section 1.2), the use of fuel cells in agricultural settings is investigated (section 5). Furthermore, the case of equipping the EPFL and UNIL sites with a digester and a solid oxide fuel cell is examined (section 6).

Apart from the actual scientific research outlined above, the main questions left are to determine the investment cost and the lifetime of fuel cells to make them more attractive than a combustion engine. For the university setting, the focus is to determine the technical feasibility of valorising the food waste on site.

1. State-of-the-art Technology

1.1 Biogas

Biogas is the result of the decomposition of organic matter into methane (CH_4) and carbon-dioxide (CO_2) through a complex biological process. Its composition is variable as it depends on the digested substrate, on the operating conditions and on the retention time.

Biogas can be the product of a gasification of organic matter as will be shown later. In order to produce and use biogas, it is necessary to understand four steps: anaerobic digestion, gas cleaning, reforming, and upgrading. These subjects are addressed in the following.
There is a public debate about whether or not biogas is a renewable resource. In fact, biogas can be both: a sustainable unlimited resource or an unsustainable resource. The decisive criterion is which substrate is used for the digestion. If the substrate is a readily available waste product (manure, food waste, organic industrial residues or agricultural waste), then the produced biogas is sustainable and can be considered a renewable energy source. On the other hand, if the substrate is an energy crop, then the biogas plant may be more harmful than beneficial to the environment[1].

The global biogas potential is estimated to lie around 36,000 PJ [23]. Knowing that the world total primary energy supply in 2012 is 556,000 PJ [24], biogas could provide 6.5% of the total.

In 2009, the European production of biogas was 335 PJ, whose provenance can be divided as follows: 52% from farm digesters, 36% from landfill and 12% from sewage [26]. Four years later, with an annual growth of 10%, the biogas primary energy production increased to 544 PJ [25]. This has been achieved with 13,800 digesters and around 7,400 MW of electricity generating capacity [27]. The European Commission is expecting this number to double, in order to reach the 20% renewable energy target in 2020 [28].

[1]the European Commission published a working document [63]on the sustainability of solid and gaseous biomass used for electricity, heating and cooling. In the section on biogas, the report highlighted the environmental issues stemming from the use of energy crops and encouraged the use of a higher percentage of manure, slurry and other organic waste to improve the greenhouse gas emission performance of biogas installations.

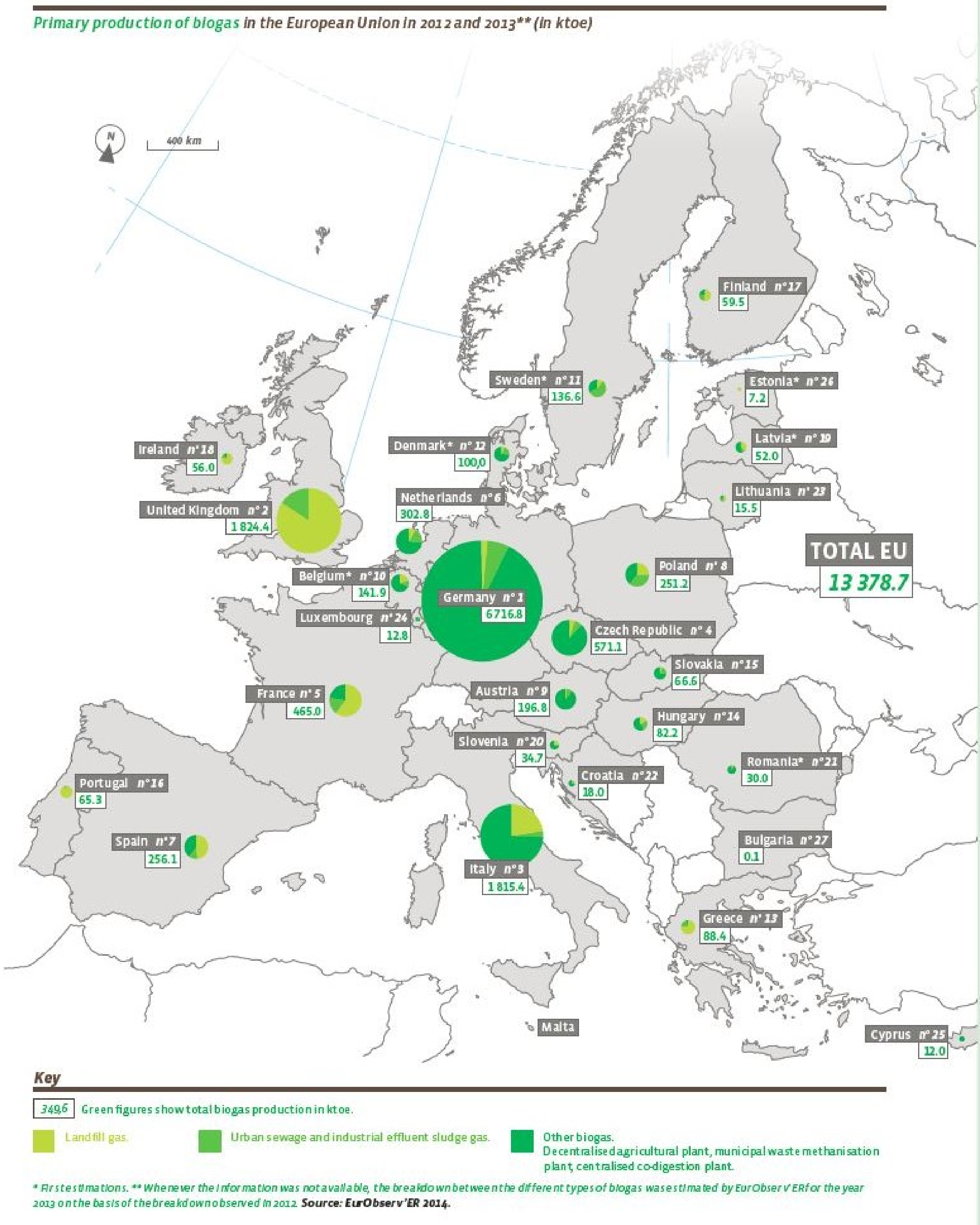


Figure 1.1: Primary production of biogas in the EU [25]

1.1.1 Substrate

The substrate is the organic matter which is decomposed to produce biogas. In fact, all organic matter can be added as substrate. The differentiation is only in the conversion method (anaerobic digestion (section 1.1.3) or gasification (section 1.1.3)).

Some parameters are important to categorise the substrate. The dry-matter content (DM), also known as the total solids (TS), is the proportion of solid content. The volatile solids (VS) content is the organic part of the dry-matter (DM) content. It is sometimes referred to as organic volatile solid (OVS). The biogas yield is either described in function of the VS or of the fresh matter (FM).

Animal manure, crop residues, organic fraction of municipal solid waste, meat processing wastes, food waste, waste water are the most important substrates for anaerobic digestion. They differ in cost, biogas yield, residence time[2], availability, inhibitor compounds and composition. An extended list with their proprieties is shown in Table A.9 in Annex A and in Figure 1.2.

Substrates	Biogas yield (Nm^3/t volatile solids)
Animal manure	200–500
Crop residues	350–400
Organic agro-industrial wastes (dairy sludge, olive mill wastewater, brewery and distillery wastes, etc.)	400–800
Meat processing wastes	550–1,000
Waste water sludge	250–350
Organic fraction of municipal solid waste (OFMSW)	400–600
Energy crop (maize, sorghum, etc.)	550–750

Figure 1.2: Biogas yield from various substrates [29]

The substrate can be decomposed into 3 main components: raw protein, raw fat and carbohydrates. Each one has different properties which make up the composition and the yield of the final biogas.

The main point for the choice of the substrate is the availability of the resource. As it is shown in Figure 1.2, some substrates have a higher yield than others (for example corn crop and food waste) but are only available in limited amounts.

If a biogas-plant operator manages to secure the safe income of a single resource (e.g. corn crop and food waste), then the plant will have to do mono-digestion. There are several drawbacks when performing a mono-digestion: technically, ecologically and economically.

First of all, the availability of organic waste is limited, thus creating competition between the biogas producers [30].

Furthermore, using energy crops like corn has a high impact on the environment and on the food production. Growing energy crops will diminish the land available for food production. This can lead to an increase in food as well as land prices [31]. Additionally, in food waste mono-digestion proteins can be present in concentrations that are high enough to destabilise the biological process. Adding a low-protein substrate in the digester, such as vegetable oil, would be recommended [32]. Nonetheless, food waste has a high biodegradability and a high methane yield compared to other substrates, thus making it desirable for anaerobic digestion [33].

[2]The residence time is the time the substrate needs to digest in the digester (same as digestion time)

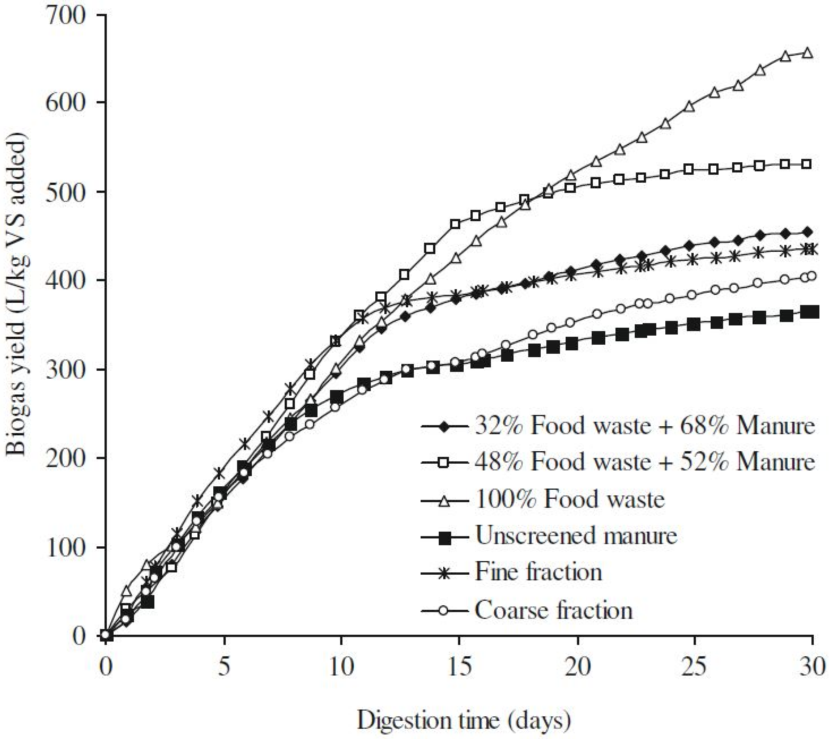


Figure 1.3: Biogas yield from various substrates as a function of the digestion time in [L/kg$_{VS}$] [34]

As can be seen in Figure 1.3, mono-digestion of manure has some drawbacks. Its degradation rate and biogas yield are low; however, it is a continuously available free resource for the farmer. Moreover, transforming all the animal wastes into biogas helps the environment by reducing green house gases. Finally, it is possible to predict manure production (and biogas production) based on cattle numbers, food served to the animals, milk production, pregnancy rates, and culling rates using prediction parameters [35]. Cabrera et al. [35] concluded that excretions are lower during September through December, medium from January through March and in August, and higher between April and July, mainly because of pregnancy rates, culling rates, and milk production. The wet manure excretion is approximately *63kg per cow per day*, according to the same study.

Based on the environmental benefits of transforming animal excretions into biogas, and on its availability in a farm, it seems beneficial to use manure as a substrate before adding energy crops. This entails that for the case study in this project, small biogas installations using mainly manure (>80%), make sense ecologically.
Co-digestion is the process of digesting different materials at the same time as it may enhance the anaerobic digestion process due to better carbon and nutrient balance as well as install positive synergism and the added nutrients can support microbial growth [37] [38] [39]. Furthermore, retention time is decreased and biogas yield can be subsequently increased by mixing the right substrates together [34] [40] [41].

If the basic elementary formula ($C_nH_aO_b$) of the feedstock is known, a maximum biogas yield and methane content can be calculated according to the Buswell equation (equation 1.1) proposed by Buswell and Hatfield (1936).

$$\mathrm{C_nH_aO_b} + (\mathrm{n} - \frac{\mathrm{a}}{4} - \frac{\mathrm{b}}{8})\mathrm{H_2O} \rightarrow (\frac{n}{2} + \frac{a}{8} - \frac{b}{4})CH_4 + (\frac{n}{2} - \frac{a}{8} + \frac{b}{4})CO_2 \tag{1.1}$$

As shown in Figure 1.3 (and in the previous table), food waste(FW) has one of the highest biogas yields; after 30 days of digestion food waste produces almost double the amount of biogas than manure (657 vs. 366 L/kg$_{VS}$). The methane yield is also higher for food waste with 353 L/kg$_{VS}$ against 241 L/kg$_{VS}$ for manure. However, biogas from manure has a higher methane fraction (66% vs 54%), this is why the biogas energy content is also higher for the manure (25 vs 20 MJ/m^3).

Approximately 90% of the biogas yield from manure can be obtained after 20 days of digestion. The food waste decomposition is a bit more linear and only about 80% of the biogas yield can be reached after the same 20 days. Here is where co-digestion comes in handy: mixing food waste with manure (32% food waste + 68% manure) makes it possible to increase the biogas yield (compared to manure) by 25% and increase the methane yield by 17%. These substantial improvements have largely been studied: during the period of 2012-2014, 50% of the publications about anaerobic digestion contained the word co-digestion, showing a real interest in the subject [42].
Furthermore, even though most biogas plants use energy crops (see Figure 1.9 for Germany) the academic world is still more inclined to study plants using manure as the main substrate (Figure 1.4).

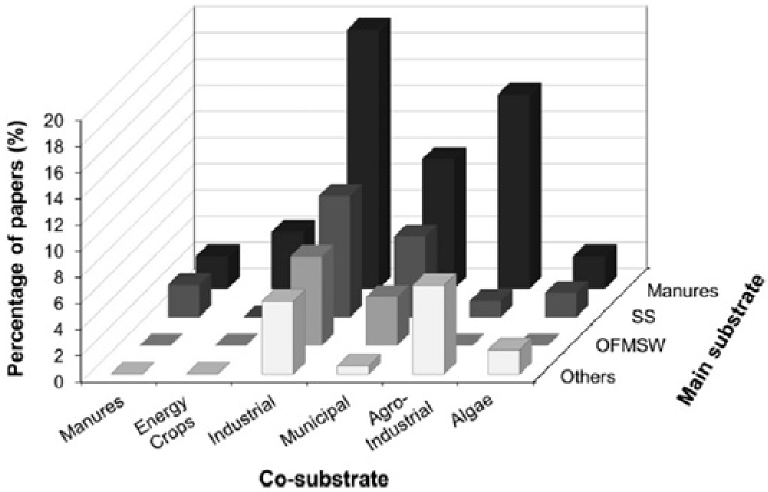


Figure 1.4: Main substrates and co-substrates in co-digestion papers in the period of 2010-2013 [42]

Another study [40] showed that the optimum substrate mixture consists of one-third food waste and two-third cattle manure. Methane production is enhanced by 41.1% (under batch tests). Additionally, co-digestion of manure and food waste enhanced the resistance to pH changes. Furthermore the higher biodegradation of lipids and C/N ratio are the main reasons for the biogas production increase.

1.1.2 Existing biogas power plants

In the next section, the existing biogas plants will be described, with a special focus on Switzerland. It is interesting to investigate the differences between them, regarding size, substrates and process.

In Switzerland, composting plants process almost half of the collected biowaste. Agricultural biogas installations treat 13 % of the 1.25 mio tons of biowaste [152]. According to the Swiss Federal Office of Energy [159], there are 32 biogas installations with an electrical power less than or equal to 100 kW (which have a feed-in tariff). From those, 7 have a power under 30 kW$_{el}$. Finally, the only ones under 10 kW$_{el}$ are a 5.1 kW$_{el}$ installation in Neuchâtel running since 2010, and a

5.5kW$_{el}$ facility in Aargau working since 2006. The complete list is presented in Annex A in Figure A.4.

The Swiss market is slowly turning to small-scale biogas: the companies start to propose compact installations, the farmers are getting more informed of the different proposed solutions and conferences are put in place to reunite them. Some commercialised biogas plants are shown below.

The compact installation of Schweizer is not a fixed product. Each plant is conceived individually and mostly with lots of civil work. The minimum capacity is 25 kW$_{el}$.

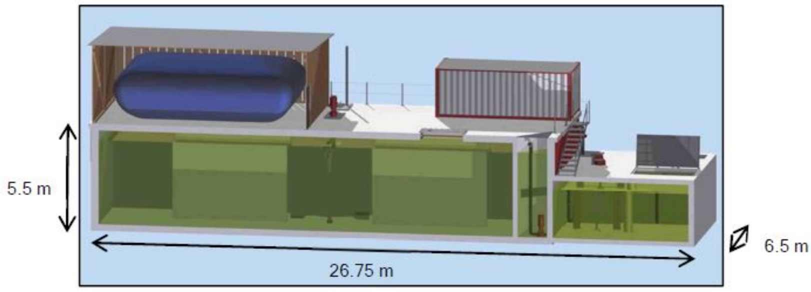


Figure 1.5: Biogas installation - Schweizer [17]

The German company Agrikomp, proposes the Güllewerk solution, which consists of two containers. The digester of 120 m^3 is situated in one of the containers and the CHP unit with the rest of the equipment in the other. The minimum power is 30 kW$_{el}$.

Figure 1.6: Biogas installation - Güllewerk [160]

The Belgian company Biolectric has a 10 kW$_{el}$ product, which can work with liquid manure.

Figure 1.7: Biogas installation - Biolectric 10kW$_{el}$[161]

The English company QubeRenewables proposes the smallest installations found. The biogas plant is in a shipping container, and the black cylinders are the pre-mixers. They propose units of 3.2, 7.5, and 14 kW$_{el}$. Furthermore, it is possible to add a digestate storage and a biogas storage, and to install two units in parallel.

Figure 1.8: Biogas installation - QubeRenewables 7.5kW$_{el}$[162]

All the above-mentioned companies have similarities in the conception of their product: the installation is mostly pre-built and comes in containers.; the digester is not made of concrete and no (or very little) civil work is necessary. Furthermore, wet digestion is always used.
A list in the annex of the report "Development of small scale biogas installation" [17] contains a collection of all the European providers of small scale biogas facilities.

In Germany, following a new policy on biogas (increased feed-in tariffs, no substrate obligation) the number of biogas installations has increased rapidly. As the next figure shows (Figure 1.9), more than 90 % of the installations use corn silage. Moreover 63% of the total amount of digested substrate in Germany is energy crops (*Nachwachsender Rohstoff "NaWaRo"*), the rest being manure. This means that the main point of these biogas plants is not to valorise agricultural waste and reduce GHG emissions, but to produce the maximum amount of electricity from a natural resource. An interesting statistic is the repartition of the installed power and the percentage of added manure.

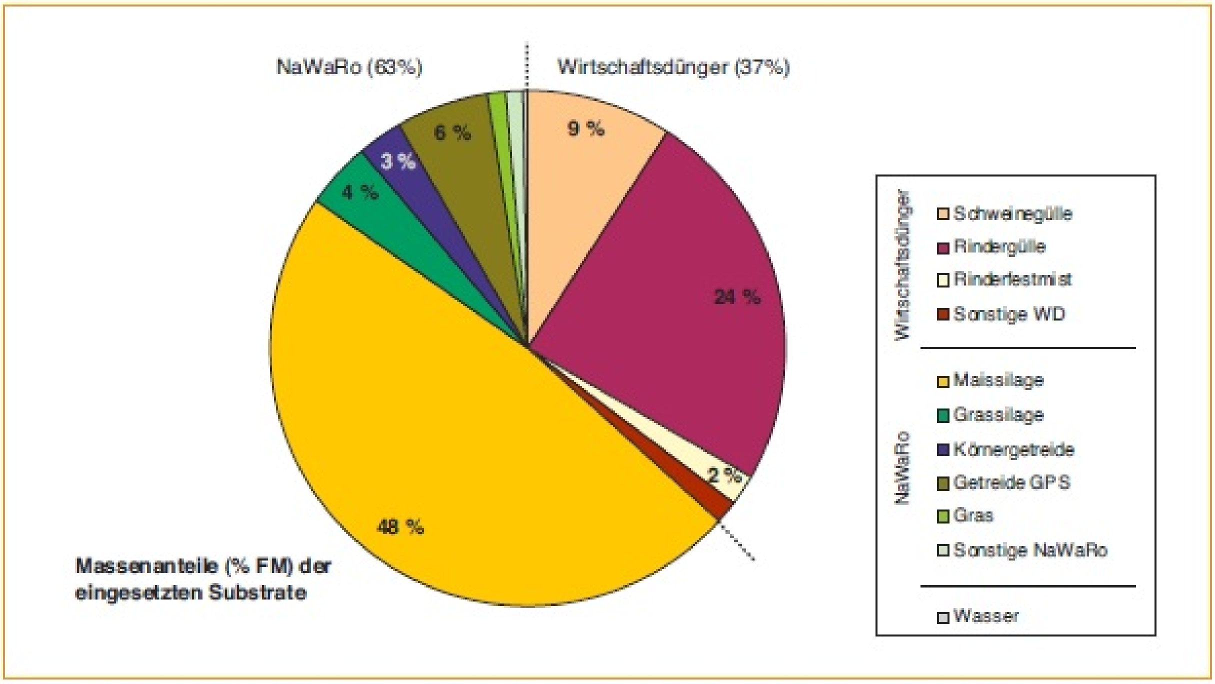


Abb. 3-1: Mittlere Massenanteile der Substrate in % FM an der gesamten eingesetzten Substratmenge aller bundesweit erfassten Biogasanlagen

Figure 1.9: Mass fraction of the substrate in % FM of the total used substrates in Germany [43]

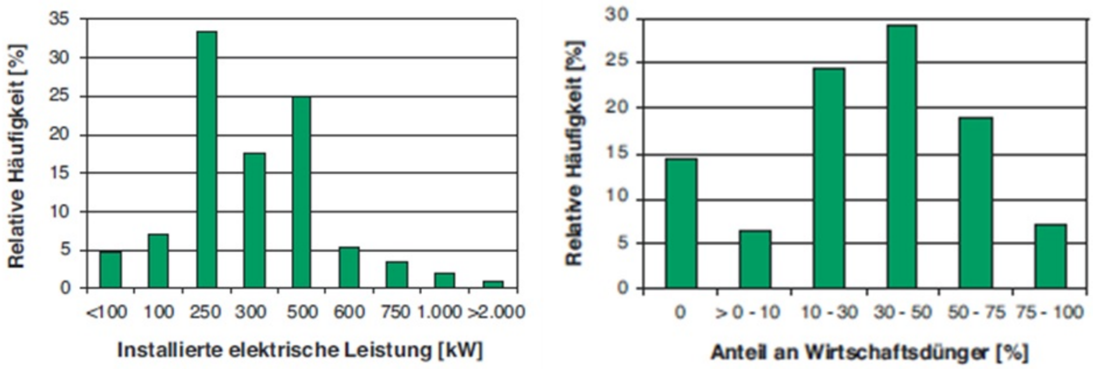


Figure 1.10: Installed power (left) and the mass fraction of added manure (right) in Germany [43]

In Germany, the average farm is bigger than in Switzerland. In fact 72% of the biogas installations are run by single farms.
The companies which are building biogas installations in Europe are presented in Figure 1.11. Germany is leading in the construction and the operation of biogas plants. Their local biogas market is more developed than the rest of Europe, which has resulted in a concentration of expertise in Germany.

Tabl. n° 4

Representatives firms of the methanisation sector in Europeat the end of 2013

Compagny	Country	Nomber of references in 2013	Electrical capacity installed in 2013 (in MWe)	Employees in 2013
AB Energy (Gruppo AB)	Italy	650	700	500
MT Energie	Germany	600	356	650
Envitec Biogas AG *	Germany	456	335	350
Biogas Weser-Ems	Germany	360	n.a.	100
PlanET Biogastechnik	Germany	330	134	< 200
Schmack Biogas GmbH	Germany	< 300	130	376
Weltec Biopower GmbH	Germany	300	76	80
UTS Biogastechnik (Anaergia Group)	Germany	176	350	125
Bioconstruct	Germany	219	123	>100
BTS Italia	Italy	178	145	125

* Including plants under construction. Source: EurObserv'ER 2014.

Figure 1.11: Representative firms of the anaerobic digestion sector in Europe - which amounts to 2.4 GW_{el} [25]

1.1.3 Digestion

Gasification

Gasification is a process in between pyrolysis and combustion. Organic or carbonaceous substrates react at high temperature above 700 ℃, without combustion, with a controlled amount of oxygen and/or steam. The result is a gas mixture, called syngas, composed predominantly of CO and H_2. The used feedstock can be coal, petroleum coke, wood, plastics, municipal waste, sewage sludge, or crops. However, this technology is not chosen for this project, mostly because the market does not offer small units. The smallest gasification technology is the E3 micro-scale biomass plant in Cheshire with 22 kW_{el} [158].

Anaerobic digestion

Anaerobic digestion (AD), or methanisation, is the decomposition of organic matter into methane (CH_4) and carbon-dioxide (CO_2) through a collection of biological processes. AD can be divided into different categories: wet or dry (solid content), batch or continuous and thermophilic (55-60℃)or mesophilic (35-40℃).

The process is composed of four reactions: hydrolysis, acidogenesis, acetogenesis and methanogenesis.

The substrate's dry-matter content (DM, also known as the total solids (TS)) defines if it will be a wet or dry AD. This difference is crucial in the conception of the digester. The most commonly used method is the wet AD, partly because liquid manure is easier to collect and in fact is the most produced substrate by farmers.

In a wet digestion, the substrate is placed in a tank and is constantly stirred by a mixer to ensure a homogeneous composition. The digester is heated to the desired range and the process takes effect.

It is possible to reduce the retention time by increasing the temperature or by having a post-digester. The relative frequency for German biogas plants is 82% for wet digestion, almost all of them continuously-fed. More than half of the plants have at least 2 digesters (62%) and more than 85% use the mesophilic range [43].

For dry digestion, the solid substrate is pushed in a box, is then heated and the "sweated" liquid (percolate) is collected and sprayed back on the top of the substrate. The retention time is usually longer for dry AD; however, as less water is present, less energy is needed to heat it up. The same amount of biogas is achieved with less volume of substrate. The resulting solid digestate has to be treated before being used as a fertiliser, but the corresponding storage volume will be smaller compared to liquid digestate.

Most of the solid digestion is exclusively done in industrial installations treating a huge amount of organic waste or energy crops. Some processes are Kompogas and Bekon, Bioferm and Kompoferm (series of digesters with discontinuous feeding of garage type), but treat a minimum amount of 10,000 tons per year.

Figure 1.12: Garage type biogas installations [166]

There are hundreds of digester designs: Silo-design, buried or half-buried, vertical or horizontal tanks, placed in a container, , the materials used range from plastics to stainless steel. Digester heating technologies vary from one plant to the other. The heat exchangers' position and design is crucial to ensure a stable process at constant temperature, without reaching a local "heat concentration". The exhaust gases of the CHP unit are usually used to heat the digester, or to pre-heat the substrate. Finally, some designs include solar thermal or photovoltaic panels to feed electricity or heat to the digester [46].

These available choices had to be considered in the developed model and different options were introduced: first the possibility to heat the digester with the solar thermal panels, the engine or the fuel cell (see section 4).

An important practical aspect of biogas plants is that the plant will usually be built bigger than what was initially planned. As Figure 1.13 shows, the plant consists of a lot of different equipments, driving the costs upwards, and by having two digesters instead of one, the biogas production will be doubled but not the overall cost. This is why small biogas installations have a harder time to find a market. One way to promote them, would be to construct digesters out of a cheaper material to reduce the costs.

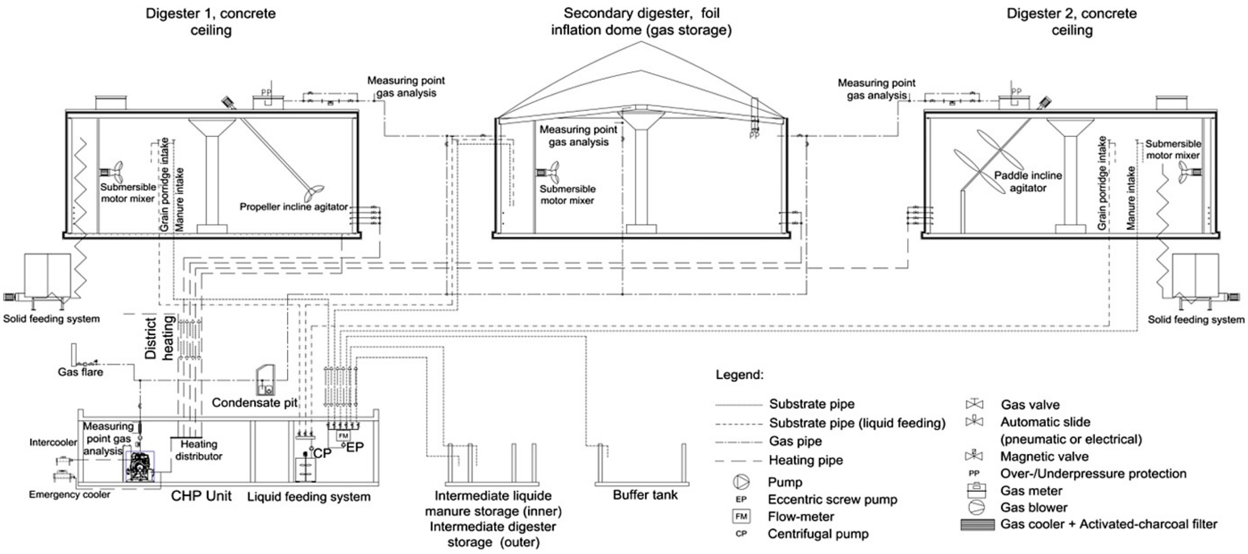


Figure 1.13: Flow scheme of a biogas plant [47]

1.1.4 Gas cleaning

Principle

After the AD, the produced biogas will not just be composed of CH_4 and CO_2. Several contaminants will be present. Most of them need to be removed. The biogas composition depends on many factors, including the substrate's composition and the operational conditions during the AD. During the planning of the installation, it is primordial to take this into account and to predict the trace compound content as precisely as possible. Some of the harmful contaminants are the result of the biological digestion while others are directly volatilised from the substrate [48].

The next figure present the possible compounds of raw biogas (Figure 1.14).

Biogas composition at the entrance to the biogas polishing system at 30 °C and 25–30 mbar(g).

Compound/trace	Family	Units	Range
CH_4	Major	%	55.1–57.8
CO_2	Major	%	28.5–32.5
N_2	Major	%	7.5–12.0
O_2	Major	%	1.8–2.9
Relative humidity (RH)	Major	%sat	100
H_2S	Inorganic Sulphur	ppm_v	104–1.852
Methyl mercaptan	Organic Sulphur	mg/m^3_{STP}	0.3–0.7
Ethyl mercaptan	Organic Sulphur	mg/m^3_{STP}	0.1–0.8
Dimethyl sulphide (DMS)	Organic Sulphur	mg/m^3_{STP}	0–0.1
Dimethyl disulphide (DMDS)	Organic Sulphur	mg/m^3_{STP}	udl(0.1)
COS	Organic Sulphur	mg/m^3_{STP}	udl(0.1)
CS2	Organic Sulphur	mg/m^3_{STP}	0.4–0.6
nC-5	Alkanes	mg/m^3_{STP}	udl(0.1)
C-6	Alkanes	mg/m^3_{STP}	udl(0.1)
C-7	Alkanes	mg/m^3_{STP}	udl(0.1)
C-8	Alkanes	mg/m^3_{STP}	0.3–1.9
C-9	Alkanes	mg/m^3_{STP}	0.7–9.2
C-10	Alkanes	mg/m^3_{STP}	22.5–33.1
C-11	Alkanes	mg/m^3_{STP}	1.9–3.4
C-12	Alkanes	mg/m^3_{STP}	0.5–0.8
Sum Linear HC	Alkanes	mg/m^3_{STP}	29.3–44.0
Benzene	Aromatic	mg/m^3_{STP}	0–0.1
Toluene	Aromatic	mg/m^3_{STP}	1.1–2.5
Ethylbenzene	Aromatic	mg/m^3_{STP}	udl(0.1)
m&p xylene	Aromatic	mg/m^3_{STP}	0.3–0.6
o xylene	Aromatic	mg/m^3_{STP}	udl(0.1)
i-propilbenzene	Aromatic	mg/m^3_{STP}	udl(0.1)
Trimethylbenzene	Aromatic	mg/m^3_{STP}	0.6–1.9
m&p-ethyltoluene	Aromatic	mg/m^3_{STP}	0.2–1.6
o-Ethyltoluene	Aromatic	mg/m^3_{STP}	0.2–0.5
i-Propyltoluene	Aromatic	mg/m^3_{STP}	udl(0.1)
Pinene	Aromatic	mg/m^3_{STP}	0.2–0.8
Limonene	Aromatic	mg/m^3_{STP}	0.6–1.2
Sum BTEX	Aromatic	mg/m^3_{STP}	3.5–4.4
Carbon tetrachloride	Halogenated	mg/m^3_{STP}	udl(0.1)
Chloroethene (Vinyl chloride)	Halogenated	mg/m^3_{STP}	udl(0.1)
Trichloroethylene	Halogenated	mg/m^3_{STP}	udl(0.1)
Clorobenzene	Halogenated	mg/m^3_{STP}	udl(0.1)
Dichlorobenzene (all isomers)	Halogenated	mg/m^3_{STP}	udl(0.1)
Trichlorofluoromethane (R-11)	Halogenated	mg/m^3_{STP}	udl(0.1)
Chlorodifluoromethane (R-22)	Halogenated	mg/m^3_{STP}	udl(0.1)
Trimethylsilanol (TMS)	Organic silicon	mg/m^3_{STP}	udl(0.1)
Tetramethylsilane	Organic silicon	mg/m^3_{STP}	udl(0.1)
L2	Organic silicon	mg/m^3_{STP}	udl(0.1)
D3	Organic silicon	mg/m^3_{STP}	0–0.8
L3	Organic silicon	mg/m^3_{STP}	udl(0.1)
L4	Organic silicon	mg/m^3_{STP}	udl(0.1)
D4	Organic silicon	mg/m^3_{STP}	4–6.5
D5	Organic silicon	mg/m^3_{STP}	6.5–9
Sum org. Silicium compounds	Organic silicon	mg/m^3_{STP}	12.6–15.3
Sum of Silicium	Organic silicon	mg/m^3_{STP}	3.5–4.5

udl: under detection limit.

Figure 1.14: Biogas composition [49]

The raw biogas needs to be cleaned, because some compounds are harmful for the environment and damage the fuel converting unit, some are toxic and have noxious effects on humans and some are corrosive. The final degree of purification depends mainly on the fuel-converting equipment (FCE) downstream in order to ensure the expected life-time and efficiency, regardless of the technology used. In general the biogas is cleaned after leaving the digester and before entering the FCE. In some rare cases, it could be possible to perform a gas clean-up before the gas is expelled into the environment, but this would mean handling a larger volume of gas, due to the addition of air in the fuel before the combustion.

It is also obvious that the digestate is contaminated by unwanted compounds since waste water sludge will bring heavy metals and organic pollutants to the digestate; terrestrial weeds and crop residues will contaminate it with their pesticides; human waste can contain viruses. Contrary to biogas, the digestate is in liquid form and the clean-up is considerably more difficult.

The main contaminant is sulphur and is principally present in its hydrogen sulphide form (H_2S). It is the most toxic contaminant. Other harmful trace compounds for the equipment or the environment are nitrogen, oxygen, halides, siloxanes and water.

The required degree of fuel gas purity is influenced by the equipment downstream, the corresponding conditioning technology is highly dependent on the biogas quality required at the outlet and on the biogas quality supplied at the inlet. Usually the gas clean-up is performed in three stages: a first stage featuring an adsorbent to remove H_2S with a usual removal efficiency of 99%; a second stage including a biogas cleaning unit to remove moisture; the last stage, which only concerns the equipment requiring a high biogas purity (fuel cells) consists of an activated carbon unit to remove remaining trace components (siloxanes, linear and aromatic hydrocarbons) [49].

Water removal

When biogas is taken out of the digester, it will be saturated with water vapour. By flowing through the pipes, the water vapour can cool down, condensate and cause corrosion. In addition, the water droplets will not only affect the pipes but also the FCE: the droplets will get stuck in the membrane of the fuel cell and block the passage for the ion-exchange, causing the whole system to shut down. The internal combustion engine (ICE) will also be affected.

Thermodynamics teaches that water can be condensed by increasing the pressure or decreasing the temperature. A simple, cheap and often performed method is to bury the gas line in the soil and to equip it with a condensate trap.

Even though water can also be removed through absorption or adsorption, it is preferable to carry out the drying before the cleaning process of the biogas: moisture adsorption may lead to a significant reduction of the active area, leading to a reduction of the adsorption capacity [49].

H_2S removal

Sulphur, mostly present as hydrogen sulphide (H_2S) is the most harmful trace component present in biogas. It is very toxic to humans and extremely corrosive for the equipment and the pipelines, and poisonous for the fuel cells. Sulphur causes corrosion on metal parts, degrades the engine's oil and the fuel cell catalysts. It also forms poisonous sulphur dioxide during combustion [101]. However, the removal processes are well-known, as the chemical and petrochemical process industries have been dealing with it for many years. The maximum levels of contamination are still debated, but 300-500 ppm_v for ICE and 1 ppm_v for FC or grid injection are good values.

The main removal techniques can be classified into three processes [101]:

- physical process: includes absorption and adsorption using solid and liquid phases
- chemical enhancement: using chemical absorption with oxidising or alkaline solutions
- biological processes: bioscrubbers (chemical H_2S absorption followed by a biological reactor for solution regeneration) and biotrickling filters (used mainly for odour control). Specific bacteria, which are growing on a wet inorganic material degrade the polluants.

The physical and chemical process have high investment and operational costs, but they are very effective. On the other hand, the biological methods are cheaper, but can only purify the biogas to a certain degree.
In the last years, most of the installations have used the advantages of both processes by having a two-stage gas-clean-up process. The first clean-up consists of a cheap biological method, followed by a fine clean-up with a more expensive physical-chemical process. In that way the cost-effectiveness of the gas-clean up is improved by a great amount.

The subject is thoroughly studied in the academic world, and a vast amount of papers have been written on the H_2S removal and in particular on the negative effects of H_2S on a SOFC. Besides, a large number of companies propose solutions such as incorporating activated carbon, iron sponges and bioscrubbers (Dirkse Milieu Techniek DMT).

When the CHP unit of a biogas installation is an ICE, the limits are higher and thus the gas-cleaning is done with less attention in some cases. One method is to inject air directly in the digester to precipitate the sulphur. It can be observed as small yellow crystals. This method is also dangerous, as the methane present in the digester could react with the oxygen. A visited installation [130] had this system, which can be visualised in the Annex A in Figures A.7 and A.8.

1.1.5 Silanes and siloxanes

Silanes and siloxanes are the second largest family of biogas contaminants. They are volatile organic silicon compounds. Mostly they appear in WWTP and landfills (in very small quantities for agricultural biogas) and can be removed using adsorption on activated carbon. Still, it is a compound which cannot be overlooked, as the formation and deposition of SiO_2 can affect many components of the fuel cell system.

1.1.6 On-line measurements

On-line measurements are vital for preserving the equipment and predicting the power production. The best installations have on-line measurements which can be checked instantaneously and the plant manager (as well as the company) will receive an alert if a parameter is not at its optimal value. More robust ones take only the elemental on-line measurements (temperature, electricity,...) and a gas-probe is manually extracted (into a TECOBAG (PETP/AL/PE 12/17/75) or in a Nalophan NA bag [50]) to perform the necessary tests.
The most important measure is the amount of electricity produced by the CHP unit. It can be directly read from an electric meter. This is also the most common measurement device present in German installations (figure A.1). More information on this subject is presented in Annex A in section A.

1.1.7 Upgrading

The poor methane content of biogas does not have a good effect on the efficiency of conventional engines and even more for transport applications, where it cannot be used. A practical solution is to "upgrade" the biogas to biomethane (also called biofuel). The biogas is enriched in methane from 50-60% to 99%. The biomethane is similar to natural gas and can be injected into the natural gas grid.
The goal is to extract the CO_2 in order to increase the methane content. This can be done using various methods: Pressure Swing Adsorption (PSA), absorption with water (water scrubbing), adsorption with chemicals, membrane separation and cryogenic separation.

The extracted CO_2 is still useful. For example, it can be used to grow algae in a pool, which capture CO_2. The algae can then be used as substrate to produce biogas, thus the circle for CO_2 is complete.

It was found that it is not economically profitable for small biogas plants (under 150 Nm^3/hour) to favour the upgrading to biomethane with grid injection. The costs are much higher for smaller plants, compared to larger biogas upgrading plants [132].

Yet, the small scale production of biogas remains interesting. In Switzerland, two pilot projects have been working since 2012. A small biogas upgrading plant of 1 - 1.5 Nm^3/hour (Blue BONSAI BB1) and a bigger one of 15 Nm^3/hour (Blue BONSAI BB15) [134].

Figure 1.15: A small Swiss biogas upgrading plant (15 Nm^3/hour) [134]

1.1.8 Digestate dehumidification

The water content of the digestate depends on the substrate. The higher the water content, the more volume will be required to store the digestate. In some remote places the duration required for digestate storage can be as high as 6 months (for hygienic and mobility reasons). This means building a large pit in concrete which is in the order of 20% of the total installation costs [17]. This substantial cost can be avoided if the digestate is dehumidified.

There are several methods to dry the digestate: one can do it through a centrifugal liquid solid separator[3] (see Figure 1.16), or the solid content could be composted, used as a fertiliser or transported elsewhere.

[3]The flow rate of the liquid is higher than the maximum supported flow rate of the separator of Figure 1.16. The farmer was handy and built this breaking device himself. This is why the pipeline is doing 3 loops. Through the friction of the curves and due to the elevation, the incoming liquid will be slower and have the required flow rate at the entry of the separator.

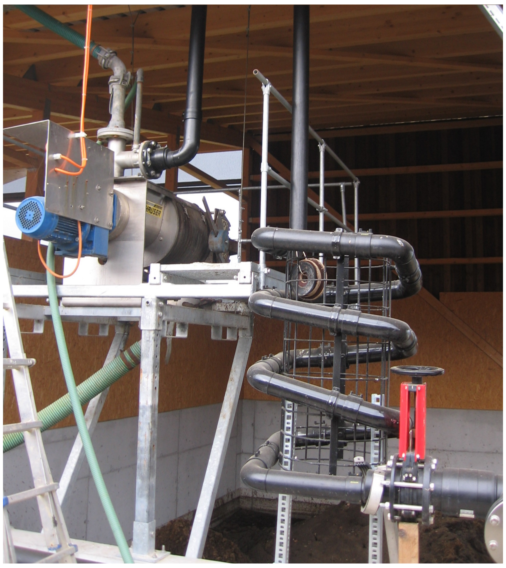


Figure 1.16: The separator in a visited biogas installation (Ackermann Cie [130])

Another way to dehumidify the digestate is through an evaporator. The special award of the Swiss association of agricultural machines (ASMA) went to a prototype system of refining liquid digestate in 2014[135]. The evaporator uses only 200 W_{therm} per litre of evaporated water and is supposed to be profitable after 2 years [136].

Figure 1.17: The digestate evaporator of Arnold & Partner AG [136] [135]

1.2 Fuel Cells

1.2.1 Principle

The first fuel cell was built in the UK in 1839 and consisted of 4 pairs of platinum electrodes immersed in sulfuric acid, which were connected to a 5th cell performing electrolysis (reverse reaction). This means that the efficiency was 25%. Nowadays, FC have the highest electrical conversion at small to medium power range for CHP units. Unlike a combustion engine, the FC bypasses the mechanical cycle through an electrochemical combustion. An ICE uses the chemical energy of the fuel through a direct combustion, producing heat that will in turn be converted to work. In a FC, the fuel (H_2, CH_4, biogas or NG) is directly converted into electricity and heat. This electrochemical process is explained in more detail in the next paragraphs.

The fuel is oxidised (combustion) in the reaction zone and an electron exchange from the fuel to an oxidant (O_2) takes place while the current is redirected to an external circuit, producing a direct electrical current (DC).

At both interfaces between electronic and ionic conductors, there is a charge transfer of electrons, and a mass transfer of molecules. The interface of the reaction zone is called the triple phase boundary, where gas (pores), catalyst (electrons) and electrolyte membrane (ions) meet.

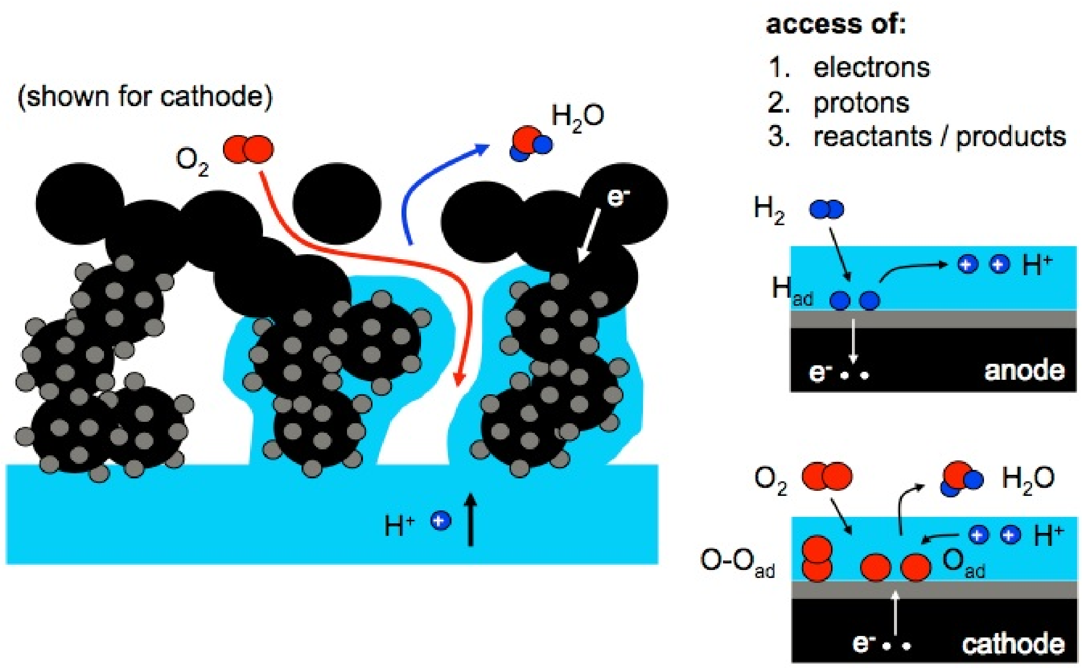


Figure 1.18: Triple phase boundary: gas(pores), catalyst (electrons) and electrolyte membrane (ions) meet [75] [76]

The advantages of FC are numerous:

- high electrical efficiency for any power size (even for small sizes 1W-1MW) and especially at partial load,
- low chemical and acoustical emissions,
- cogeneration (production of heat and power),
- modularity,
- fuel flexibility (it is possible to feed a FC with fossil fuels (NG, diesel, coal gas) and with renewable fuel),
- better use of fossil fuels (because of higher efficiency).

The fact that the FC's efficiency is higher at partial load than at full load can be explained with Figure A.2 in Annex A.

1.2.2 Different fuel cells and combination with biogas

The fuel cells are classified into 5 groups depending on their electrolyte. They are presented in the next table:

Type	Electrolyte	Temperature	Fuel	Power size	Application
AFC	Alcaline solution	20-100 °C	H_2	20 kW -200 kW	Transport (vehicles, buses)
PEFC	Polymere membrane	20-100 °C	H_2 & methanol	0.1 W - 100 W	electronics
				1 kW - 100 kW	Small Cogen.
				20 kW - 200 kW	Transport (vehicles, buses)
PAFC	liquid acide	20 °C	H_2 & NG	0.2 MW - 3 MW	Medium Cogen.
MCFC	Molten salt	650 °C	C_xH_y	>1 MW	Transport (ships)
				0.2 MW - 3 MW	Medium Cogen.
SOFC	Solid ceramic	600-1000°C	C_xH_y	1 kW - 100 kW	Small Cogen.
				>1 MW	Transport (ships)
				0.2 MW - 3 MW	Medium Cogen.

Table 1.1: The differences between the FC [76]

The only FC which can use directly NG, biogas, and any hydro-carbonated fuels are the MCFC and the SOFC. Hence these are the best choices for a combination with biogas. It is worth mentioning that in the late 1990s, PAFCs were used with biogas (after an upgrade to biomethane). This trend has been ceased since the appearance of the higher temperature fuel cells (MCFC and SOFC). Mostly this is due to carbon oxide (CO), which is a poison for the FC at low temperature but a fuel at high temperature (it has to removed from the gas in an extra step) and, due to the upgrading process of the biogas to biomethane or the reforming to H_2 at low temperatures, which is also not necessary at higher temperatures.

For more information on the differences between the fuel cells, consult Figure A.5 in Annex A.

The molten carbonate fuel cell is a galvanic cell with a liquid electrolyte of alcalicarbonate. The poor current density and the CO_2 recirculation impose a minimal size on the MCFC (250kW). The electrical efficiency varies from 30 - 50% with a total system efficiency (thermal and electrical) of around 90% [97] [100]. The main companies which produce MCFC are FuelCell Energy (from the US, models of 300 kW, 1400 and 2800, electrical efficiency of 47%) and POSCO Power (from South Korea).

1.2.3 Reforming

The process of reforming transforms the fuel (NG, Biogas or C_xH_y) to a syngas composed of H_2, CO and CO_2. The low temperature FC needs this reforming step prior to the injection, in contrast with the higher temperature FC (MCFC and SOFC) which can have an internal reforming (due to faster cinematics).

On the other hand, the injection of pure methane without internal or external reforming into a high temperature fuel cell would cause carbon depositions, which would destroy the stack. Hence, a reforming step is always considered if a FC is fuelled with something different than hydrogen.

The basic chemical reactions to consider for the reforming are the following:

- Steam Reforming (STR) is an endothermic reaction (see equation 1.2). Water in vapour state is mixed with the methane to form hydrogen and carbon monoxide. It shows the highest H_2 yield (80-90%) [76], as well as the lowest operation temperature. However, the reforming system needs to be connected to a demineralised water source, which can be problematic in some cases.

$$\text{Steam Reforming (STR):} \quad CH_4 + H_2O \Leftrightarrow 3H_2 + CO \tag{1.2}$$

- Dry reforming (equation 1.3) is the reaction explaining why the CO_2 present in biogas is an intrinsic reforming agent. Less steam addition is needed (if a STR is performed). CO_2 reacts endothermically with the methane to form carbon monoxide and hydrogen.

$$\text{Dry Reforming:} \quad CH_4 + CO_2 \Leftrightarrow 2H_2 + 2CO \tag{1.3}$$

- Partial Oxidation (POX) (equation 1.4) is in reality a combustion followed by STR. This is why the H_2 yield is lower(60-75%) [76], because part of the fuel is already oxidised (hence the name). It is a simple, fast and exothermic reaction but there is still a risk of carbon deposition. In practice, air instead of O_2 is injected into the methane.

$$\text{Partial Oxidation (POX):} \quad CH_4 + 1/2O_2 \Rightarrow 2H_2 + CO \tag{1.4}$$

With STR, high CO and H_2 concentrations can be reached (for biogas and methane). Comparing POX for CH_4 and for biogas, less heat has to be transferred to the reformer in the case of methane (see Figure 1.19). The reason lies with the influence of the endothermic dry reforming reaction of biogas. However, the ability of methane to produce rich concentrations with POX is limited by the carbon formation boundary (see Figure 1.20)

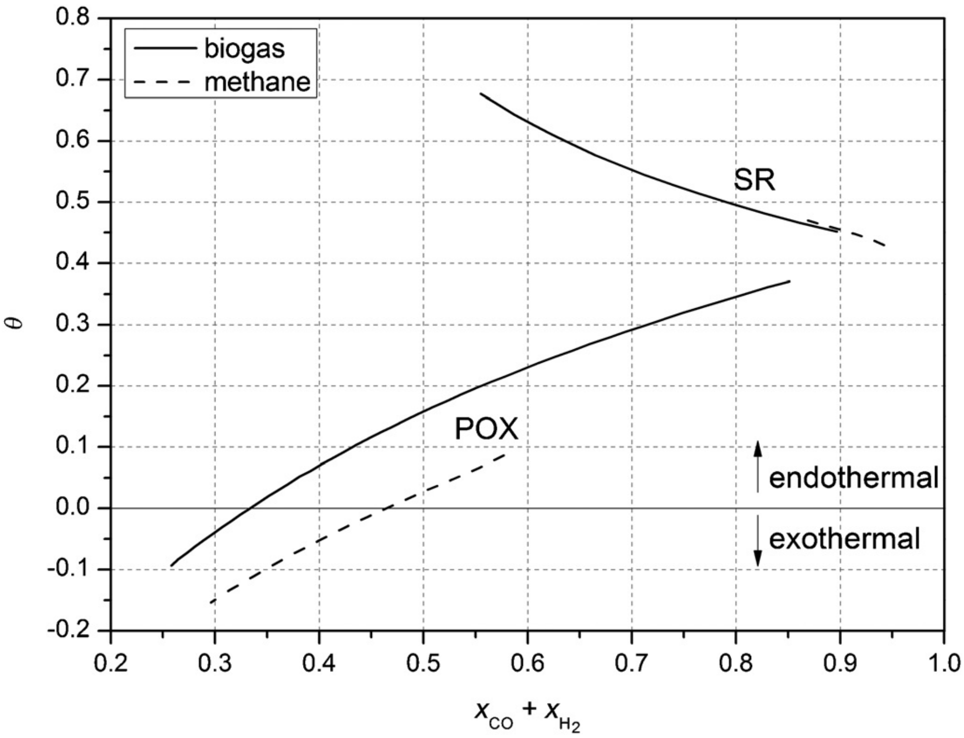


Figure 1.19: Dimensionless heat flow θ in dependence of cumulated H_2 and CO concentrations for partial oxidation (POX) and steam reforming (SR) of biogas and methane,[dimensionless heat flow θ : relation of enthalpy change within the reformer to the chemical power fed to the reformer] [96]

- Finally autothermal reforming (ATR) is an intermediate behaviour between STR and POX. It shares the advantages and disadvantages of both. The efficiency is therefore around 75-85% [76].

$$\text{Autothermal reforming ATR:} \quad CH_4 + xO_2 + yH_2O \Rightarrow H_2, CO \tag{1.5}$$

At high temperature, CO is a fuel and not a poison (as it is at low temperature). The reforming reactions are always superimposed with the exothermal water gas shift reaction.

$$\text{Water gas shift (WGS):} \quad CO + H_2O \Leftrightarrow H_2 + CO_2 \tag{1.6}$$

The problem of carburisation (formation of carbon deposits) occurs at high temperature and they are due to the next three equations. As it is detailed in Figure 1.20, methane presents a higher risk than biogas. However, it is possible to avoid it by adding H_2O and/or O_2.

$$\text{Pyrolysis (cracking):} \quad CH_4 \Rightarrow 2H_2 + C \tag{1.7}$$

$$\text{Boudouard reaction:} \quad 2CO \Rightarrow CO_2 + C \tag{1.8}$$

$$\text{Reverse gasification:} \quad CO + H_2 \Rightarrow H_2O + C \tag{1.9}$$

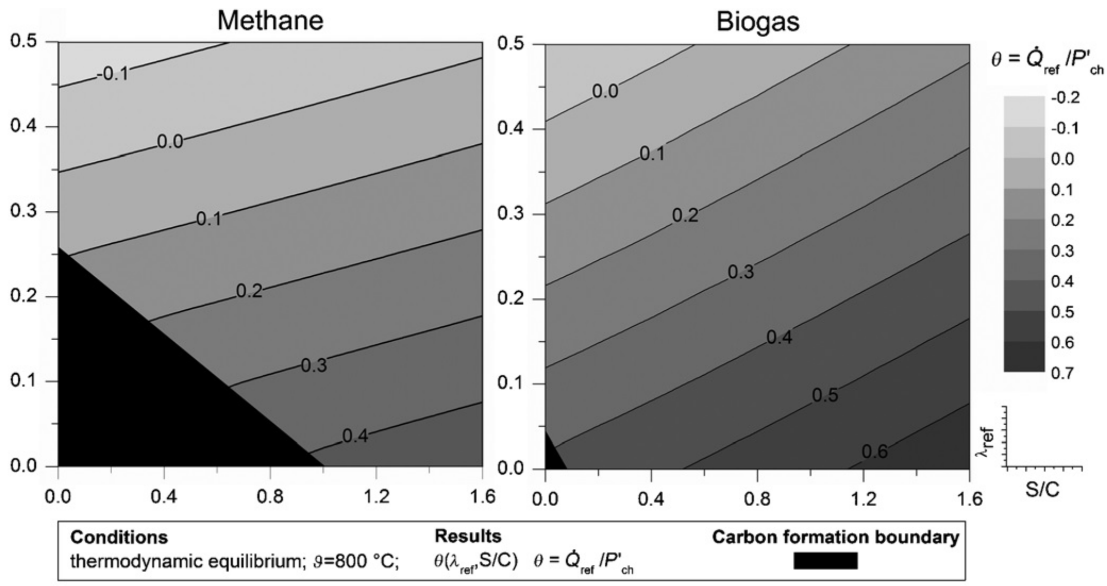


Figure 1.20: Balance of thermal energy of the reforming step at 800 °C [dimensionless heat flow θ relation of enthalpy change within the reformer to the chemical power fed to the reformer, S/C Steam to Carbon ratio, λ_{ref} air ratio (to stoichiometric needed value)], [96]

System energy integration

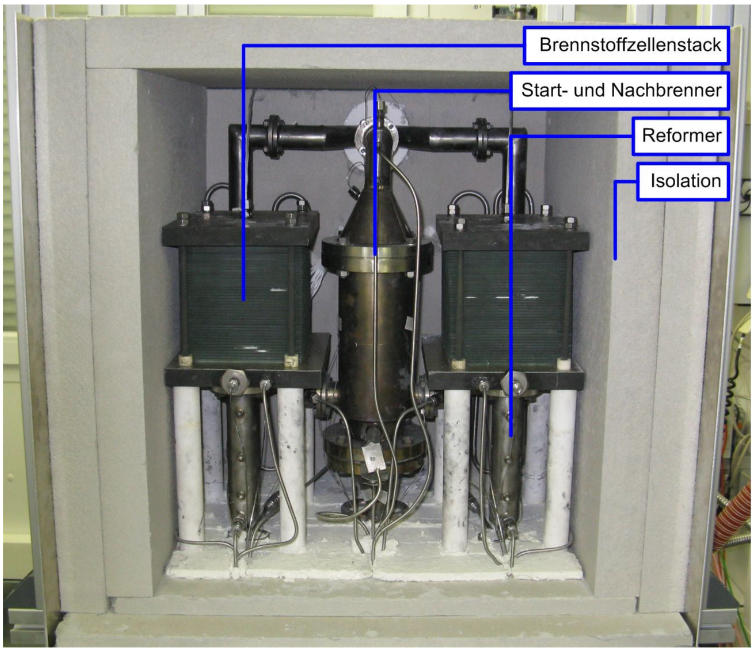


Figure 1.21: System construction of an external reformer onto a SOFC (Brennstoffzellenstack=Fuel cell stack, Start- und Nachbrenner=starter- and afterburner), [97]

There are different possible constructions for the reformer. It can be built internally or externally (see Figure 1.21), containing a recirculation of the exhaust gases to heat the reforming step; it depends largely on which FC is used and which reforming process has been chosen.

1.2.4 SOFC in-depth analysis

The SOFC is the latest fuel cell to become commercially available. The unit sizes vary from 50 W to 500 kW with high electrical efficiencies of 30 - 70%, with a total system efficiency of around 90%. The principle of the SOFC is explained schematically in Figure A.3 in Annex A along with the chemical reactions that occur for each fuel.

Nippon Oil, TOTO and Kyocera have already installed a few hundred installations in the small power sizes 0.5 - 2 kW. ENE-FARM is the first-in-the-world commercialisation of PEFC-based CHP system in 2009 followed by SOFC system in 2011. By March 2013, 37,000 units have been installed [111]. Furthermore, CFCL, developed a SOFC with an internal steam reforming, which achieved around 60% efficiency. In the smaller power spectrum there are: Wärtsilä (20-50kW), Bloom Energy (50kW), which proposes also higher power units, Delphi 5 kW (which can be run with biogas) with an electrical efficiency of 40 - 50 %, EBZ (which can be run with biogas) 1.5kW with an electrical efficiency of 35%, SOFC Power 0.8kW (28% guaranteed with biogas in 2012 [99]) and Staxera-EBZ 2.2kW (30% guaranteed with biogas in 2012 [99]).

The high electrical efficiency on all power sizes and its higher tolerance for different fuel and harmful components, its flexibility and high modularity make the SOFC the best choice to be coupled with biogas.

Figure 1.22: BlueGEN SOFC (1.5 kW 60% electrical efficiency), SOLID Power [137]

The limits of contaminants for an SOFC are (data from SOLID Power [131]):

H_2S:	1 ppm
HCl:	1 ppm
NH_3:	5000 ppm
Halogens:	1 - 5 ppm
Silica:	0.01 ppm
VOC:	0.5 – 1.0 %

The literature on the limit values, on the effect of each component and on their removal is very complete and should be consulted for more information.

FC (and specifically SOFC) with biogas

The history of FC coupled with biogas started in 1997, during which the first plants were installed [107]:

- 1997-1998 Toshiba operated a PAFC (200kW) during 5000h with biogas derived from a STEP in Japan. [112] [113]
- in the USA, the New York Power Authority operated during 7000h a 200kW PAFC 1997-1998 with biogas from a WWTP. [114]
- another PAFC of 200kW was tested on two landfill sites in Los Angeles in 1995 and in Connecticut 1996. [115]
- the first PAFC in Europe fuelled with biogas was inaugurated in 2000 (Cologne, Germany). [107]

A first $1kW_{el}$ SOFC demonstration stack (from the Swiss manufacturer HEXIS) was installed as a pilot program at an agricultural biogas installation [107] in Switzerland in 2000. This was probably the first Swiss SOFC-Biogas facility.
Using this as a starting point, a series of papers have been published around biogas coupled with a small-size SOFC, studying mainly the incidence of the model parameters on the efficiency [105] [106] [107].

It would take too long to summarise everything that has been done on the subject FC-biogas since then. However, the main points are resumed below, focusing on agricultural biogas and SOFC's.

- In 2008, Fraunhofer IKTS unveiled a 1 kW SOFC running on agricultural biogas, coupled with an external reformer using POX and a gas cleaning system [91]. It is believed to be the first biogas plant to run purely on waste instead of edible raw materials.
- A thermodynamic calculation indicates that dry reforming of biogas will yield reformate of great quality [93]. By having an effective thermal coupling of the reformer, it is possible to apply low air-to-fuel ratios down to λ_{ref}=0.05.
- A lab-container carrying an SOFC stack (1.3kW, 38 % electrical efficiency) fuelled by biogas is installed next to a farm by Heddrich et al. [94]. The stack has operated for 500 h. Active coal is used for the cleaning and the maximum reached efficiency was of 43.9% (see Figure A.9 for a picture of the installation).
- Another project has been aimed at the study of the feasibility of running biogas (syngas in this case) with an SOFC short stack at lab-scale level. An H_2S contamination was included to study its effect. After 500 h of operation, results clearly reveal that a SOFC stack can be successfully operated with a contaminated gas mixture (comparable to biogas). [95]
- A further study has revealed that there is no need to add external water, as the biogas has a high CO_2 content. It is sufficient to add only a very small amount of air for POX, but a large quantity of heat is needed in the reforming step "to increase the chemical energy content of the fuel, supplied by the afterburner". With this process, a high value of electrical efficiency (51%) is found. [96]
- The number of publications, books and articles on SOFC-biogas is vastly increasing. Some interesting books should be mentioned, as one featuring FC combined with waste management (Fuel Cells in the Waste-to-Energy Chain [18]) and another complete series solely on biogas (The Biogas Handbook). [98]
- European projects dealing with SOFC-biogas start to appear (in 2009): the first one from 2009 to 2012 called BIOCELL [99], studies the feasibility, the environmental impact and the economical viability of energy production from biogas via both PEMFC and SOFC adapted to WWTP. Furthermore different cleaning technologies are studied and a technico-economical evaluation of both different available commercial technologies for biogas cleaning and biogas energy conversion systems is done. The installation of two pilot plant (with biotrickling filter and polishing system (see Figure 6.9)) should help to develop adequate tools for an industrial implementation [49] [101].
- This project resulted in the publication of several papers describing the installation and the obtained results: the summary of the biogas clean-up and the SOFC pilot plant is also described in the paper published by N. de Arespacochaga et al. [102]. It consists of a commercial 2.8kW SOFC powered with cleaned sewage biogas for around 700h in a WWTP. The average electrical and thermal efficiencies are of 34% and 28%.
- Another paper by N. de Arespacochaga et al. [103] compares the current applicability and limitations of biogas-powered MCFCs and SOFCs and compares them with ICEs and MTs. MCFCs have shown the highest technical performance (improving the electrical self-sufficiency of the WWTP of around 60% compared to conventional cogeneration units). Until now, ICEs are still the most economically profitable alternative, with payback periods of FC systems being four times larger. The conclusions point at the high investment cost and the low stack durability of the FC which need to be improved for industrial deployment in WWTPs [103].

- A similar European project was started in 2009 called BIOSOFC, which also studied the feasibility of biogas fuelled SOFCs. Two 5 kW_{el} SOFC were installed reaching an average electrical efficiency of around 25% [110].
- More recently (2014) a publication investigated the thermodynamic performance of a 2.5 kW_{el} small-scale SOFC fuelled with biogas. The highest electrical efficiency of 56.55% is reached under STR, the highest total plant efficiency is achieved under POX (74.14%) (because exothermic reforming reactions increase thermal output). The conclusion is that ATR is a suboptimal reforming option [104].

1.3 Conventional engines

Practically all the biogas installations are equipped with gas engines (except for a few cases of micro-turbines). The next figure (Figure 1.23) shows the relative frequency of the used CHP units in German biogas facilities. Only two different systems are used: gas engines or dual fuel engines. The latter is a modified diesel engine specially designed to work with biogas. Though it is more efficient, the conventional gas engine is still the most popular with almost 70% of biogas plants having at least one installed.

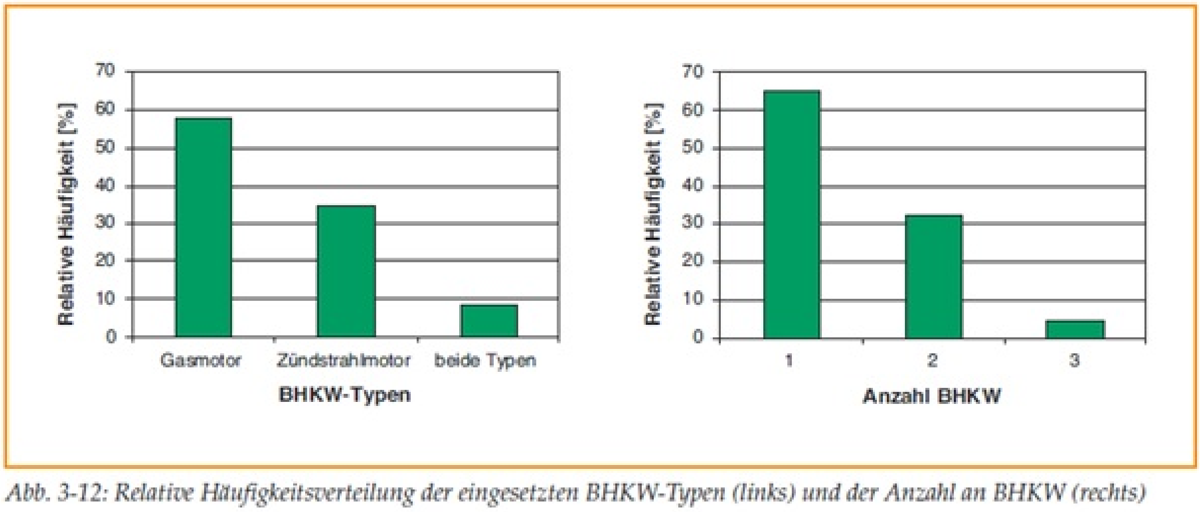


Figure 1.23: Relative frequency of gas engines, dual fuel or both (left) and the number of CHP-units (right) in German biogas installations [43]

The ICE are cheap (compared with FC), but their electrical efficiency which is between 20-45% depends on their size. The efficiencies of engines of several biogas installations have been collected in Figure 1.24. The small-size ICEs present low electrical efficiency. ICEs under 100 kW_{el} have efficiencies below 35%.

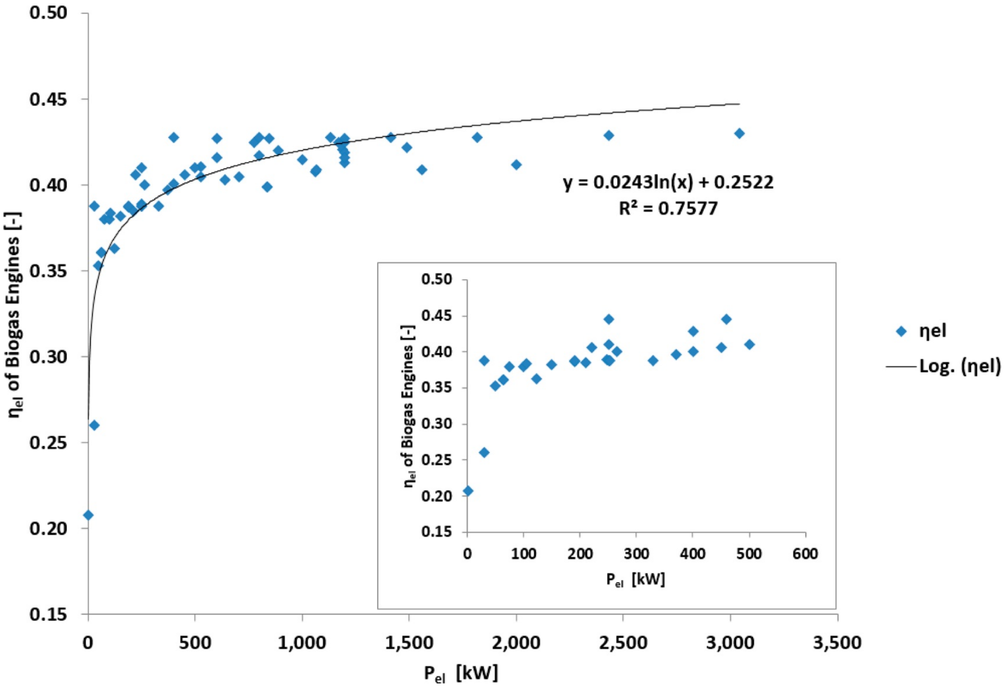


Figure 1.24: Electrical efficiency of biogas installations - [104]

There is a real potential for FCs in low power applications, as this is the only market share where the ICEs are weak (in efficiency). Only a few manufacturers propose engines with a capacity below 10 kW_{el}. There are even less under 5 kW_{el}.

In the next table (see Table 1.2), the most important small engines are listed with the related electrical efficiency, as mentioned by the manufacturer.
It is important to keep in mind that the ICEs performance was measured with natural gas. The efficiency might be lower when using biogas.

Manufacturer / Model	Electrical Power kW_{el}	Electrical Efficiency [%]	Thermal efficiency [%]	Total efficiency [%]	Reference
Kirsch nano	1.9	19	76	95	[139]
Vaillant ecoPOWER	1	26.3	65.7	92	[141]
Yanmar CP5WN-SNB	5	28	56	84	[143]
AISIN Seiki	6	29	56	85	[144]
EC Power XRGI 6	6	30.6	63	93.6	[145]
Flow Boiler	1	~10	82	92	[146]
KraftWerk Mephisto G 16+	5-16	31.5	69.5	101	[147]

Table 1.2: Characteristics of different small-sized ICE based on the lower heating value of natural gas

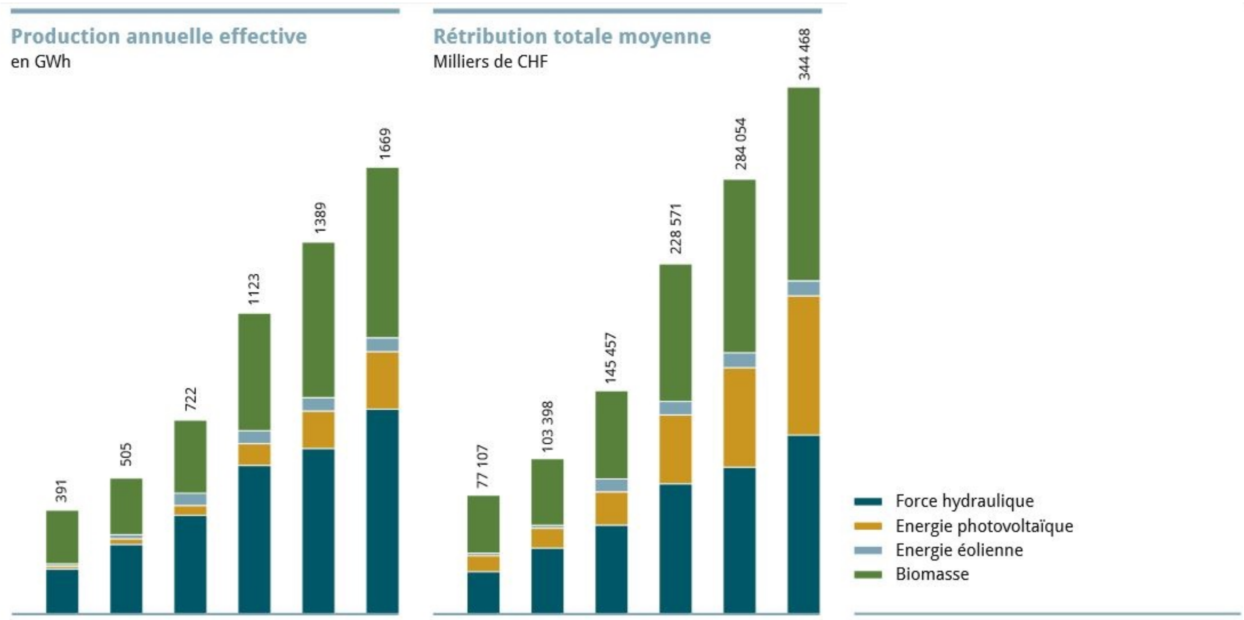
2. Feed-in tariffs and financing helps

As most renewable energy sources are not profitable in their early stage, feed-in tariffs may be introduced to promote them. The feed-in remuneration is the selling price of the electricity that the state agrees to pay for a determined duration (usually 20-25 years). Some governments also provide a financing help for the initial investment in the form of a zero-interest loan or give a fixed remuneration in order to promote the initial investment.

The feed-in tariffs will define the plants' profits and fix the economic value of the project.

2.1 Switzerland

In Switzerland, the feed-in-tariffs are called the RPC (fr: *rétribution à prix coûtant du courant injecté*) and are available for photovoltaics, wind, and biomass. Biomass is the biggest receiver of government contribution in 2014 (see Figure 1.15) after PV. There are 233 plants receiving biomass feed in tariffs, accumulating a total power of 213 MW_{el} and a production of 636 GWh (electric and thermal) (see Figure 2.1) [118].



2009	2010	2011	2012	2013	2014	2009	2010	2011	2012	2013	2014	
166.4	259.5	369.2	554.1	617.9	766.2	27 310	42 879	57 775	84 840	95 893	116 769	Force hydraulique
15.4	21.2	34.1	83.9	139.3	214.4	10 967	14 420	22 043	45 159	65 266	91 435	Énergie photovoltaïque
5.1	12.9	44.4	47.1	51.2	52.6	955	2 407	8215	8761	9668	9824	Energie éolienne
203.6	211.6	274.2	437.6	580.5	635.9	37 875	43 692	57 424	89 811	113 227	126 440	Biomasse
391	**505**	**722**	**1123**	**1389**	**1669**	**77 107**	**103 398**	**145 457**	**228 571**	**284 054**	**344 468**	**Total**

Figure 2.1: Annual effective production and average government contribution for renewable energies under the RPC [118]

Usually, the government revises the feed-in tariff each year, and this mostly to decrease it. The latest values for PV systems are the following:

	Nominal power of the installation			
	0 - 1.9 kW	2 - 9.9 kW	10 - 29.9 kW	$\geqslant$ 30 kW
Compensation:	none	Single payment	Right of option	RPC

Table 2.1: Compensation for a PV power plant in Switzerland - 2015 [116]

The right of option is the choice between a single payment or the feed-in tariff. The single payment (called rétribution unique (RU)) is a help on the investment and cannot exceed 30% of the total cost.

This raises the question of profitability, especially in the light of over 35,000 projects waiting to be supported financially. The choice between which kind of financing help should be applied for is made difficult because the waiting time for such financial assistance can go up to a few years. An OFEN information report advises to opt for the single payment as there are objectively very small chances to benefit from the feed-in tariff (RPC) if the power lies in the range between 10 and 29.9 kW. The next Swiss feed-in tariff reduction will take effect 1^{st} April 2016 and 1^{st} October 2016 [117].

Category	Power [kW]	RPC [cts/kWh]
Open field	$\leqslant$ 30	23.8
	$\leqslant$ 100	19.8
	$\leqslant$ 1'000	19.2
	$>$ 1'000	17.2
Mounted on rooftop	$\leqslant$ 30	26.4
	$\leqslant$ 100	22.0
	$\leqslant$ 1'000	21.3
	$>$ 1'000	19.1
Building-integrated	$\leqslant$ 30	30.4
	$\leqslant$ 100	25.3

Table 2.2: Feed-in tariff (RPC) for solar panels (PV) in 2014 [119]

The single payment is paid in function of the installed power. For a 9 kW installation, the average contribution will be CHF 5,900 paid in the 20 months after the completion of the PV plant. A 29 kW PV plant will benefit from CHF 15,900 [121]

For biomass the RPC is the following in Switzerland:

	Nominal power of the installation				
	$\leqslant$ 50 kW	$\leqslant$ 100 kW	$\leqslant$ 500 kW	$\leqslant$ 5 MW	$>$ 5 MW
Basic compensation [cts/kWh]:	28	25	22	18.5	17.5
Agricultural bonus [cts/kWh]:	18	16	13	4.5	0
Heat bonus [cts/kWh]:	2.5	2.5	2.5	2.5	2.5
Maximum [cts/kWh]:	48.5	43.5	37.5	25.5	20

Table 2.3: Compensation for a biomass power plant in France - 2012 [120]

A few minimal requirements are necessary: the installation must meet a minimal electrical efficiency, and the thermal needs of the installation must be met by the CHP or by a renewable energy source. The compensation is given for 20 years. The agricultural bonus (from Table 2.3) is acquired if at least 80% of the substrate is manure. The heat bonus is given if 20% of the produced heat is used outside the installation. [120]

The initial investment can be financed in part by the zero-interest loan given by the Confederation (under the Ordonnance sur les améliorations structurelles (OAS)). It is fixed at a maximum of 50% of the initial value or CHF 800,000.

Apart from government financing, such a project can also receive partially financing aid from a bank. In the report "Developing small agricultural biogas units "[17] a potential financial plan is presented: 50% of the investment is being borrowed from the government, 45% is lent by a bank with a 3,5% interest rate, 5% are invested by the farmer him-/herself. A discussion with a banker [157] confirms the interest rate, which usually lies between 2.5-4.5% for a similar project depending on the farmer's guarantees, the average being 3.5%. However, she made clear that the farmer's own investment has to be around 30%.

The "Manuel Qualité Biogaz" [122] gives further information about the planning, the dimensioning, the financing and the operation of a biogas facility.

3. Economic analysis

The economic performance indicator of this study is the net present value (NPV). The NPV is the total value of a project discounted to the present.
The NPV is defined in such a way that a negative value means that a profit is made, a positive value means that the project loses money. This redefinition needs to be made, as the linear programme minimises a variable. This way, minimising the NPV results to maximising the revenues of an installation.
It is defined as:

$$\begin{aligned} \text{NPV} &= \text{PV(costs)} - \text{PV(benefits)} \\ with &: \\ \text{PV} &= \sum_{n=0}^{N} PV(C_n) = \sum_{n=0}^{N} \frac{C_n}{(1+r)^n} \end{aligned} \tag{3.1}$$

PV is the present value of the sum of the cash flows C_n. n is the year of the cash flow, and r is the interest rate. It is possible to annualise the NPV, meaning that the cost or revenues of the project will be paid each year until the project lifetime.

$$\text{ANN} = \text{NPV} \cdot \frac{i \cdot (1+r)^m}{(1+r)^{m-1}} \tag{3.2}$$

with m being the project lifetime.
The levellised electricity cost (LEC) represents the cost to produce electricity. If the feed-in tariff is higher than the LEC, then the project will be profitable.
It is defined as :

$$\text{LEC} = \frac{\text{C}_{\text{annualised}}}{\text{E}_{\text{elec prod yearly}}} \tag{3.3}$$

with $\text{C}_{annualised}$ the total annualised cost of the project.
The total investment cost of each unit depends on the project and unit lifetime: e.g. if an installation is supposed to run for longer than the CHPs lifetime, then a supplementary CHP unit will be bought and sold when the project ends. A straight-line depreciation is used to calculate the salvage value (i.e. the expected price of the unit), which is supposed to be zero at the end of its useful life.
Equation 3.1 is used to determine the total investment cost if additional units need to be bought, and the next equation (Equation 3.4) determines the salvage value.

$$\text{SV} = \frac{(\text{LT}_{\text{unit}} - (\text{LT}_{\text{project}} - \alpha \cdot \text{LT}_{\text{unit}}))}{\text{LT}_{\text{unit}}} \cdot \frac{\text{IC}_0}{(1+\text{r})^{\text{LT}_{\text{project}}}} \tag{3.4}$$

with SV the salvage value, IC_0 the investment cost at time 0, LT the lifetime expectancy, and α the minimum amount of units to buy (round-down($LT_{project}/LT_{unit}$)).

The cost for each unit has been estimated based on existing literature.

3.1 Biogas

The cost of biogas is difficult to estimate. There are large differences between each country. In Germany, for example, the cost of biogas is lower than in France even though they use the same technology and sometimes even the same suppliers.

Germany and France :
In Germany, the median investment cost is 1,155,000 €, with an median power of 495 kW.
In France the numbers are very different: the median cost is 1,266,000 €, thus higher than the German one, but the median power is 198 kW, less than half the German one. These numbers make more sense when the tonnage is taken into account: in Germany the median is 8,700 tons per year, in France 7,515 tons per year. This means that the cost should not be compared with the power, but with the substrate. For example, the ratio cost/power is on average 3,294 €/ kW_{el} in Germany and 6,313 €/ kW_{el} in France.
If the ratio (cost/volume of the digester) is to be compared, then the installations are very similar: 537 €per cubic meter for Germany and 494 for France with the average values (411 and 393 with median values).
The fact is that in Germany, the most used substrate is energy crops (and in particular corn), which have a higher energetic density than manure or organic wastes, which are the most used in France. Hence, a German installation processing 5,000 tons a year will have a power of 160 - 200 kW, because of the highly methanogenic energy crop. In contrast, a French installation managing the same amount of substrate, but using manure, will typically have a power of around 100 - 140 kW.
Still, it is easier in the used programme to couple the cost with the power output, which enables to foresee the price and estimate the costs. Furthermore, the report indicates that the highest ratio investment cost / power found was 9,424 €/ kW_{el}, and the lowest 3,885 €/ kW_{el}.

Another interesting fact, is the division of the investment cost in its individual fractions. The civil work is almost half of the costs in the German installations. This is because of the large size of their plants, needing a high amount of concrete and materials to build big digesters and storage pits.

	Germany	France
Civil work	46%	33%
Technical	32%	49%
CHP	22%	17%

Table 3.1: Division of the investment cost for Germany and France [154]

Switzerland :
The report from the OFEN on small-scale biogas plants [17] estimated the cost for a Swiss facility. The total investment cost for an electrical power ouput of 25 kW is estimated to be CHF 800,000. The largest contribution is the civil work. This is in accordance with the previous analysis on Germany.

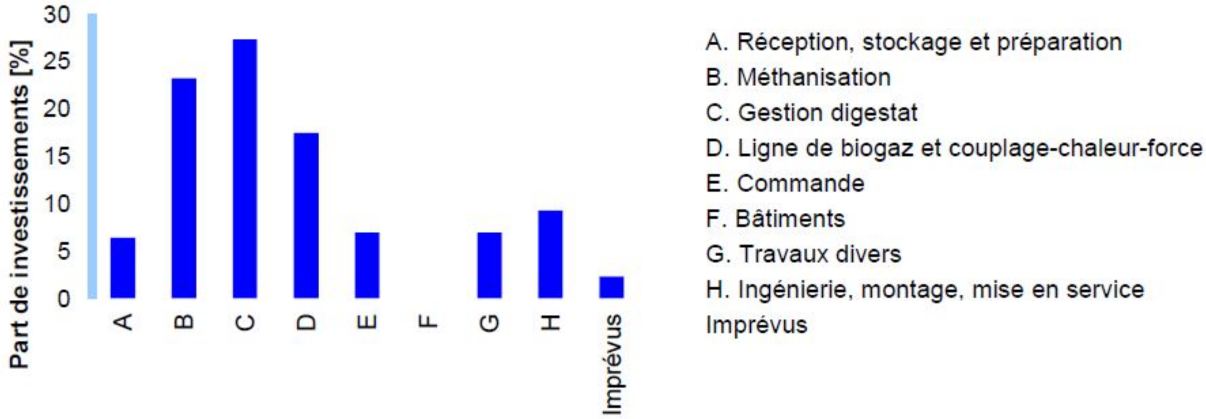


Figure 3.1: Division of the investment cost for Switzerland, [17]

Based on data presented in Table 3.2, the cost of a Swiss biogas installation is estimated. The last element in the section for Swiss installation is a facility in Trub , which was partly built by the farmer himself, hence the costs are low. The cost of the CHP unit has to be excluded. It is difficult to fix a value for the biogas cost, as it can vary largely from one installation to the other. Keeping in mind that the prices may be higher for smaller plants and deducing the cost of the CHP, the investment cost of a small-scale biogas plant is chosen at 10,000 CHF/kW$_{ch}$. For the conduction of a sensitivity analysis, values of 6,000 and 8,000 CHF/kW$_{ch}$ will be considered. In general, the cost of biogas plants in Switzerland is considerably higher than in Europe.

P [kW$_{el}$]	C [CHF]	c [CHF/kW$_{el}$]	ε_{el} (est.)[%]	c [CHF/kW$_{ch}$]	ref
		Swiss biogas installations			
50	681,700	13,032	35	4,561	[165]
80	1,500,000	18,750	37	6,938	[130]
25	800,000	18,750	30	9,600	[17]
25	~700,000	28,000	30	8,400	[169]
30	~450,000 (self-b.)	15,000	30	4,500	[169]
		Others			
10 (BE)	100,000	10,309	25	2,577	[156]
65 (LUX)	~350,000	5,384	35	1,885	[164]

Table 3.2: List of investment costs for biogas installation, P Power, C total cost, c specific cost, ε_{el} estimated electrical efficiency

All the studies made on the subject conclude that it is not profitable to build a small installation if the feed-in tariff does not increase [17] [165].

The economic analysis of a small plant is usually done by downsizing a bigger installation. But the manufacturers have become creative and found ways to reduce cost by redesigning the entire process. An example is the cost of the pits, which is high, because of the civil engineering and the expensive concrete. In small plants concrete is unnecessary and the pits and digester can be replaced with plastic or metal containers. This is the easiest solution to reduce an important part of the total investment cost.
Another aspect is the strict Swiss regulation on biogas, which some designs might not pass and subsequently it could take years to benefit from the feed-in tariff. This amount of work and waiting time can be discouraging for a farmer, even more so if the plant is small and does not yield much.

It is important for the government to invest in small stations for various reasons. The full potential of the biomass of small farmers needs to be utilised and distributed power sources will reduce grid losses which can amount to 7% of the total of the produced electricity. Finally, the market in Switzerland is enormous, there are about 20,000 farms in Switzerland that could install a biogas plant, which could create jobs and bring additional revenues to the farmers.

3.2 Equipment costs

The specific cost of the different equipment is presented below.
The cost of the deep biogas clean-up is assumed to be part of the SOFC cost, as it will be changed. Besides the biogas treatment is estimated to be between 2 - 10 % of the total investment cost [103] [49]. Furthermore, the biogas facility will also consist of a first stage clean-up, which is necessary for the ICE.

	ICE		
Kirsch nano (1.9kW) [139]	$capex_{ICE}$	CHF/kW_{el}	6,357 [140]
Kirsch nano (4kW) [139]	$capex_{ICE}$	CHF/kW_{el}	3,671 [140]
Vaillant ecopower (1kW) [141]	$capex_{ICE}$	CHF/kW_{el}	7'832 [142]
ICE capex chosen	$capex_{ICE}$	CHF/kW_{el}	6,000
ICE omex chosen	$omex_{ICE}$	CHF/kWh_{el}	0.025 [17]
	SOFC		
BlueGEN (1.5kW) [137]	$capex_{SOFC}$	CHF/kW_{el}	21'300 [138]
SOFC capex chosen	$capex_{SOFC}$	CHF/kW_{el}	20'000
SOFC omex	$omex_{SOFC}$	CHF/kW_{el}	250 [79]
	Biogas		
Biogas capex chosen	$capex_{biogas}$	CHF/kW_{ch}	10'000
Biogas omex chosen	$omex_{biogas}$	CHF/kWh_{ch}	200 (est.)
Personnel	$personnel_{biogas}$	CHF	7'280 [17]
	PV		
PV capex	$capex_{PV}$	CHF/kW_{el}	2'500 [79]
PV omex	$omex_{PV}$	CHF/kWh_{el}	36 [79]
	Battery		
Battery capex	$capex_{battery}$	CHF/kWh	1'000 [79]

Table 3.3: Summary of the costs

4. Methodology

The aim of this study is to analyse the necessary criteria for a profitable biogas/SOFC installation, depending on different initial conditions. In that sense, a biogas installation is broken down into its two main components (digester and CHP unit). The performance of the digester, which is influenced by its electricity and heat needs, is estimated and its influence on the overall profitability is evaluated. The biogas production is fixed by the size of the farm.

The goal is to compare the net present value of valorising biogas through an engine, a fuel cell, and a fuel cell PV combination. A representation of the process, consisting of the transformation of the substrate to electricity, the different CHP units, and of the studied combinations, is shown in Figure 4.1.
The following sections explain the conversion from the number of animals to biogas, from biogas to electricity and heat, and from energy to services.

4.1 Animals → biomass → biogas

The biogas potential is estimated based on the number and type of animals at the farm, and by its size. A farm's biogas yield is only determined precisely if specific measurements are done on the manure's quality (VS, TS, methane yield) and quantity (mass per day, volume), on the available co-substrates, and on the farm's logistics. The extensive excel file [155] developed by Biomass Energie, is helpful to evaluate the profitability of a potential agricultural installation. However, to keep things simple, average values will be used for the determination of a farm's biogas potential.

In that regard, the biogas potential of the farm is calculated using a simplified method described in a report commissioned by the Swiss Federal Office of Energy (SFOE) [17]. A summary of the report is available in Annex A.

The biogas yield is calculated in function of the number of milk cows and cattle, their age, the type of barns, and the size of the exploitation.

The majority of Swiss farmers have dairy cows (55%), own land in the sizes of 10-25 ha and have an average herd size of less than 20 dairy cows[1]. More than 35.9% of them are situated in plain areas but would still produce 49.7% of the global biogas potential [17]. Thus, the reference case in this study is constituted by a farm of 15 ha in plain territory with a herd size of 20 dairy cows. The reference case represents the average Swiss farm. There are 20,000 similar farms in Switzerland constituting the biggest market potential. Together they have a biogas potential of 4,400 GWh per year.

Cabrera et al. [35] studied the seasonal variation in manure excretion in dairy cows. They developed a prediction model based on herd characteristics (milk production, pregnancy rates, and culling

[1] Of the 17,775 farms having dairy cows, 38% own between 15-20 cows, 25% own between 20-25 cows, and 14% own between 25-30 cows

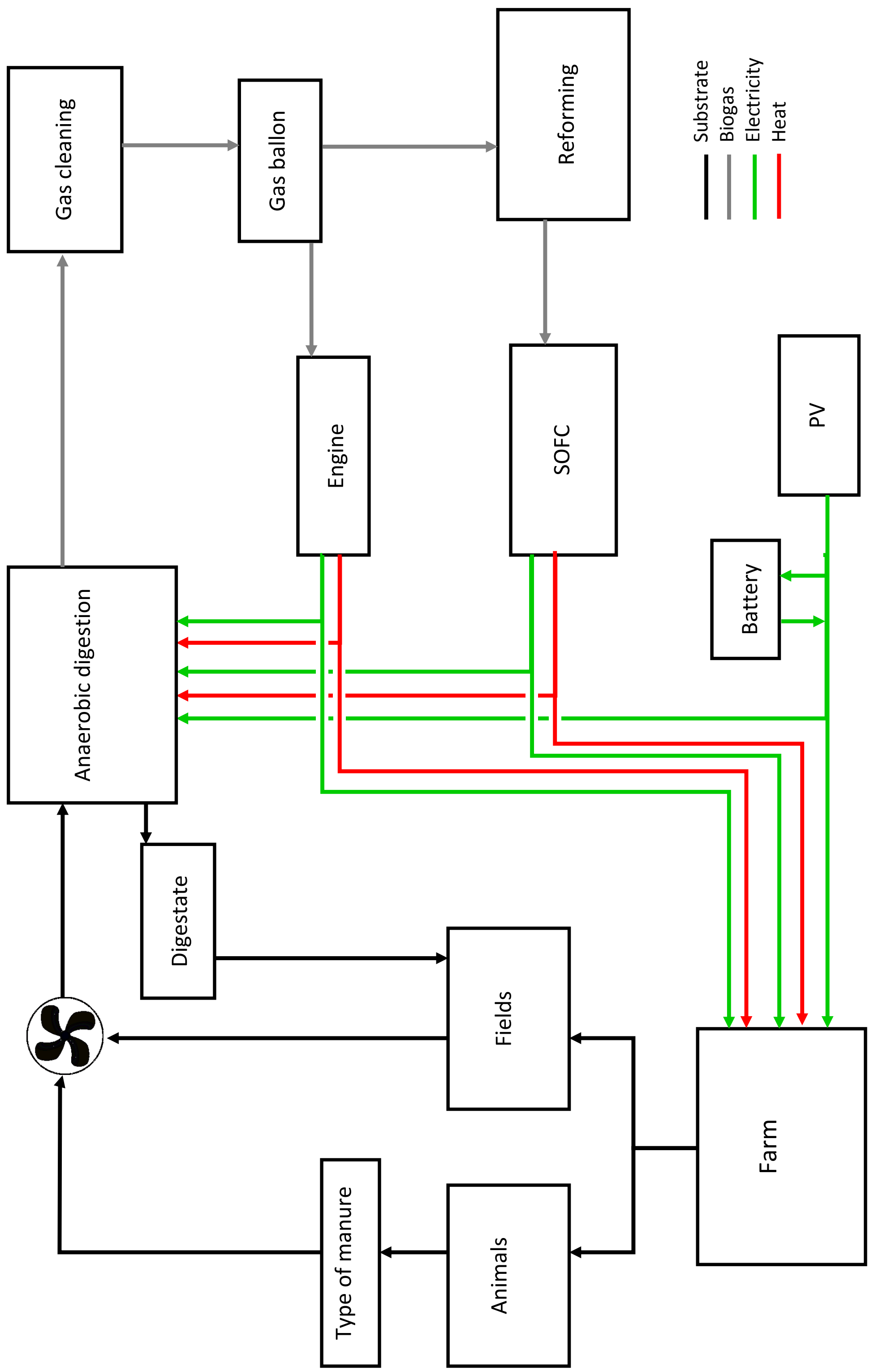


Figure 4.1: Schema of the studied biogas installation and the different tested scenarios

rates), and found a deviation of ± 3% from the monthly average (the daily average is 63 kg/cow). However, the "spring flush" (a sudden increase of the milk production levels), hot summers, or cold winters can have a significant influence on the manure excretion (± 20%), making the prediction more complicated and imprecise. A discussion with a farmer (producing biogas only with manure), who is situated in an area similar to the one considered here [156], has led to the conclusion that the biogas production can be approximated to be constant throughout the year. It is thus assumed that the biogas production of a continuously fed digester is constant.

4.2 Biogas → electricity

The biogas can be utilised in various technologies as described in chapter 1 and some are more efficient but more expensive than others. Those considered are a combustion engine (ICE) and a fuel cell (FC), where each one is implemented as a cogeneration unit and the performance indicators of the plant are studied in function of various parameters.

The digester and the auxiliary equipment have heat and electricity requirements: the mixers, the agitators, the fans, and the pumps are the biggest electricity consumers. They are followed by the CHP control unit, the auxiliary power unit, and the gas cooler [83].

It is difficult to determine the electricity needs, as they depend highly on the manufacturer of the plant and on the optimisation of the installation. Conversations with farmers [156] [130], a study on the same subject [83] and an OFEN report [17] give an idea on the order of magnitude of the self-consumption - around 8.5 - 15 % of the produced electricity is consumed by the installation, which amounts to 2.6 - 4.5 % of the biogas chemical energy (with an ICE of 30% efficiency). The conservative ratio of 15% is used in the model. The heat is needed for the digestion process, which largely depends on the ambient temperature and on the optimisation of the heat flows. Based on the report on biogas commissioned by the OFEN [17], 60 % of the produced heat (by an ICE with 53% thermal efficiency) is injected into the digester, representing 31.8 % of the biogas chemical energy. The latter is used in the model, but both will be subject to a sensitivity analysis. Usually the heat and the electricity are provided by the CHP-unit. Another possibility is to install PV for the electricity needs, and solar thermal panels for the heat requirements. Theoretically, the cheapest is to provide the electricity with the grid and the heat with the CHP or a NG-fed boiler. But this is not legal in Switzerland, where both requirements need to be supplied either by the CHP or by a renewable energy source(in contrast with France where this is legal), hence it is not used in the model. The user can either let the model find the optimised solution, or define which technology feeds the digester in heat and electricity.

The digester heat and electricity needs are defined with a simplified method. The literature shows that the electricity consumption is more or less constant over a year and is proportional to the quantity of added substrate. The heat needs, however, depend on the substrate's initial temperature, the ambient temperature, the digester's insulation degree, and the used material. All of the previous are needed to establish a heat transfer model and estimate the required heat.
However, too many parameters have to be defined and they all depend on the construction specification of the biogas facility, which can vary from one to the other.
In this project, only three parameters are used to predict the heat requirements: the ambient temperature, the desired substrate final temperature, and the proportion of the biogas chemical energy needed to heat the digester. The first two are easily defined and the latter depends on the efficiency of the biogas installation.

The required heat at each time ($\dot{Q}(t)$) depends on the substrate (T_D) and ambient temperature (T_{AMB})(see equation 4.1).

$$\mathrm{\dot{Q}(t) = k \cdot (T_D - T_{AMB}(t))}\ ; \quad \forall \mathrm{t:}\ \mathrm{T_D \geq T_{AMB}(t)} \tag{4.1}$$

The parameter k is unknown and accounts for the thermal losses of the digester.
The proportion of the biogas chemical energy annually needed for the digester is the parameter ρ, the biogas chemical energy is E_{Biogas}. ρ accounts for both the heat required to warm up the incoming substrate and the heat losses of the digester (based on the underlying assumption that the incoming substrate is at ambient temperature).

$$\begin{aligned} &\Rightarrow \Sigma\dot{\mathrm{Q}}(\mathrm{t}) = \mathrm{Q} = \mathrm{k} \cdot \Sigma(\mathrm{T_D} - \mathrm{T_{AMB}}(\mathrm{t})) = \rho \cdot E_{Biogas} \\ &\Leftrightarrow k = \frac{\rho \cdot E_{Biogas}}{\Sigma(T_D - T_{AMB}(t))} \end{aligned} \tag{4.2}$$

The value of k is inserted in equation 4.1, and the heating requirements at each time step are known.

ρ is the most important parameter - it indicates the optimisation of the installation. Its value can be reduced by heating the incoming substrate with the outgoing digestate in a pre-heater.

4.3 Energy → services

The electricity can be used either by the farmer or can be injected in the grid. The produced heat will most likely not be shared (a few cases exist where the heat is sent to nearby industry or houses) and will be used locally for the domestic hot water or for space heating.
The high feed-in tariffs in Switzerland make it profitable to sell the produced electricity and buy cheap electricity from the grid.

If the biogas installation is built for the sale of electricity at a feed-in tariff (which covers all the Swiss installations) and not for the self-sufficiency of the farm [2], all the electricity is sold and the heat is used locally (minimum of 20% required in Switzerland). The electricity needs of the farm don't need to be considered in that circumstance. This is the case that is studied.

In practice, as the heat-requirements of the digester are dependent on the ambient temperature, the installation will use, during the winter, most of the available heat for the digester. During summer, excess heat is produced and cannot always be utilised. Likewise the farm's heat requirements are small during summer, hence the excess heat is sometimes used for hay drying. This option requires the investment of a drying facility and is not taken into account here.

4.4 Linear model

The dimensioning and the control of the various units is determined by a linear optimisation problem developed by Lauinger [79]. In addition to the units already included in his model, a digester and an engine were modelled.

The linear programme expresses the methodology in a mathematical language. For more information and details about linear programming and the modelling, refer to [79] and [81].

The main changes made to the programme are the following:

[2] This cases are found in countries where the feed-in tariff is very low, for example a farm in Belgium installed a 10kW$_{el}$ biogas installation for this purpose [77]

Units:
An anaerobic digester is added, with the characteristics given in section 4.2. The SOFC and engine can work on natural gas or on biogas. The general case will be that the programme will optimise when to inject which fuel in each unit; it is, however, also possible to fix only one fuel per unit.

Finally a distinction can be made between the electricity produced from biogas and from natural gas, as this will determine its selling price.

Biogas:
First of all, there is the possibility to add a biogas facility, which consists of a digester, a storage pit, the personal and insurance costs, the civil work and all the auxiliary equipment surrounding the facility (except the CHP unit). The biogas potential is either considered as a variable or is fixed. To fix it, the parameters described in section 4 need to be set (number of cattle, type of manure, area of exploitation, etc.). The potential is then calculated and will determine the amount of biogas available.

The source of the digester's energy needs are also a variable of the problem. The user can either decide to fix the source of each demand (heat and electricity) or let the linear programme choose the optimal solution.

Sensitivity analysis:
The effect of the most important parameters on the result is analysed. The user defines upper and lower bounds on the parameters that should be analysed in detail. Then the linear programme will be executed repetitively with each distinctive value of the parameters. For a better understanding and representation of the results, only two parameters are analysed at the same time.

5. Results and analysis of the scenarios

Three scenarios, for the Swiss agricultural setting, are explained in detail and their results are presented. The scenarios consist of a farm producing biogas from manure and a small proportion from co-substrate. The conversion of the produced biogas to electricity will be done by a combustion engine (Scenario 1) or by a solid oxide fuel cell (unlike Scenario 2 and 3). A special case is analysed, in which the digester's electricity needs are not covered by the CHP unit (Scenario 1 and 2), but provided by PV panels coupled to a battery (Scenario 3).
The main results are the following: if the investment price of the SOFC is reduced to 13,000 CHF/kW$_{el}$ with a lifetime of 12 years, then it becomes competitive with an ICE. The installed PV panels help to increase the profits by 9.2 % and 16% more electricity is produced than with the SOFC alone.
It is important to diminish the biogas investment cost to 6,000 CHF/kW$_{ch}$, else no combination becomes profitable. The potential of a farm twice the average size, is better suited to target economical feasibility - a SOFC, with a 50% electric conversion efficiency on biogas, an investment cost of 8,000 CHF/kW$_{el}$ with a lifetime of 8 years would be sufficient to yield returns from the installation.

As SOFC is an emerging technology, the initial investment cost is likely to change rapidly. This is why a sensitivity analysis is conducted to estimate when it becomes more attractive than combustion engines. The lifetime of the fuel cell is varied, in order to examine if it is more profitable to develop long-lasting SOFCs than short-lived cheaper ones. Furthermore, the electrical efficiency of the FC, the investment cost of a biogas installation, and the efficiencies of the digester are varied. The performance indicator is the net present value (NPV) of the project. It covers the revenues and the costs of the installation over its life-cycle. In order to make the SOFC attractive, either the lifetime cost must go down or the feed-in tariff must go up. However, based on a conversation with the head of Biomasse Switzerland [32], this is unlikely to happen in the next couple of years. Which is why the analysis focuses on the cost with a constant feed-in tariff.

5.1 Scenario N1 - Farm with engine-biogas

The first scenario consists of a biogas installation which is combined with a combustion engine. The produced electricity will be sold on the grid at a feed-in tariff instead of being directly used. It is assumed that the heat stream leaving the ICE is injected in the house-tank and is used when available.
For the average Swiss farmer, it is not profitable to install this combination: the levellised electricity cost is 1.46 CHF/kWh$_{el}$ with an ICE of 1.9 kW$_{el}$.

The heat and electricity needs of the digester are covered by the CHP unit. Almost all the worldwide biogas installation fall into this category (a few use micro-turbine and a handful fuel cells). A schema describing this scenario is presented in Figure 5.1.

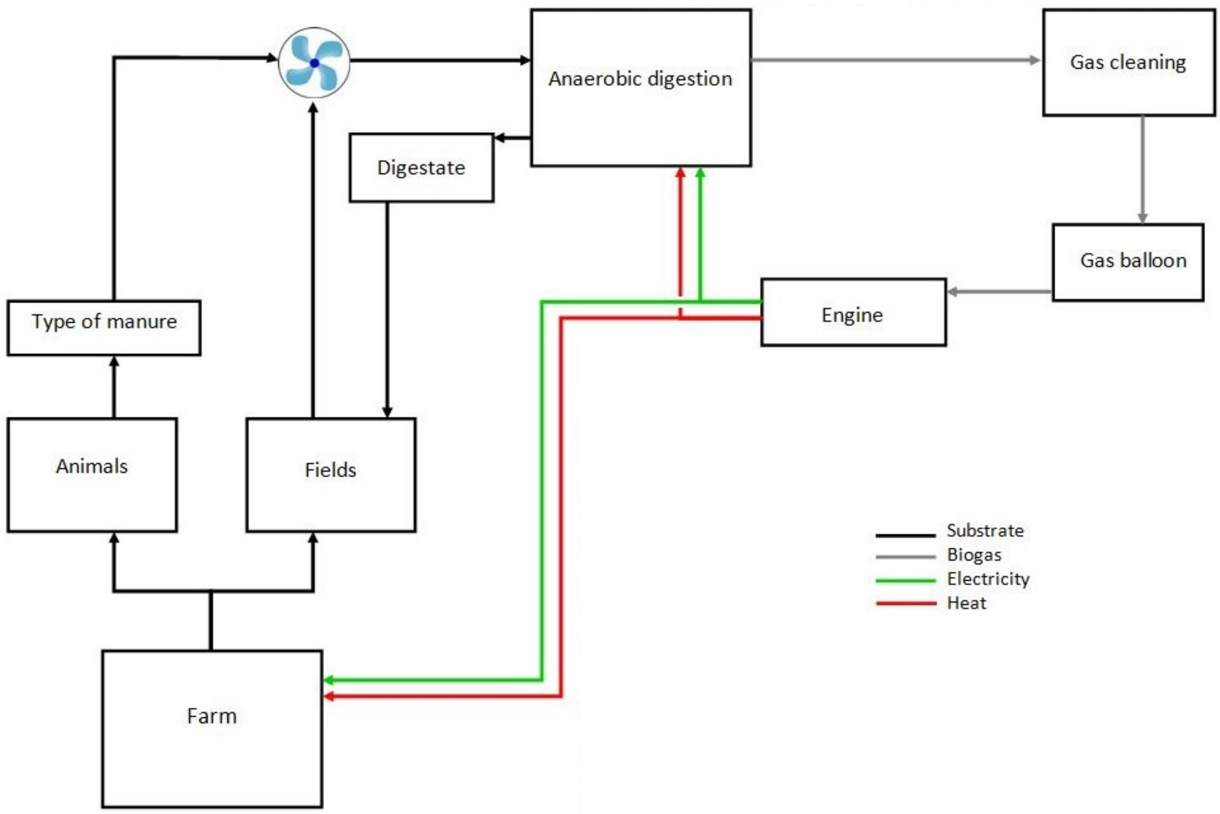


Figure 5.1: Schema of scenario N1 - see Figure 4.1 for the full schema

The already mentioned report about Swiss farms and biogas installations from the OFEN [17] did an economical analysis for a 25 kW_{el} installation, comparable to the one studied here. The results are the following:
A biogas installation of 25kW_{el}:

- Investment cost of CHF 860,000,
- 27% (of the investment) is for the storage of the digestate,
- around 24% for the digester,
- around 17% for the biogas line and the CHP unit,
- Operating costs of CHF 52,040 per year,
- LEC of 0.646 CHF/kWh,

The average Swiss farm is taken as a reference case, however the size is also made variable as to analyse its effect on the aim. The ICE cost is also subject to variations and will affect the NPV of the project.

It is assumed that all the produced heat (by the ICE) could be and is used. The already installed boiler (using NG) will not need to warm the same amount of water. The fuel cell uses the LHV value of NG, the boiler the HHV. This is because it recuperates the heat released during the water condensation originated by the water vapour created during the combustion (HHV). The HHV of

NG is 10.79 % higher than its LHV, the price of NG [CHF/kWh] differentiating both will have the same proportionality.
The savings are calculated using equation 5.1:

$$\begin{aligned} \text{Savings} &= \frac{\text{H}_{\text{ICE}}}{\varepsilon_{\text{Boiler}}} \cdot \text{c}_{\text{NG HHV}} \\ \Leftrightarrow \text{Savings} &= \frac{\text{H}_{\text{ICE}}}{\varepsilon_{\text{Boiler}}} \cdot (\text{c}_{\text{NG LHV}} \cdot (1 + 10.79\%)) \end{aligned} \tag{5.1}$$

First of all, the digester heating requirements need to be implemented, as described in equations 4.1 and 4.2. The coefficient ρ from equation 4.2, which describes the ratio of the biogas chemical energy that needs to be injected in the digester, is set at 31.8% according to the OFEN report [17]. Figure 5.2 represents the relation between the ambient temperature and the heat needs of the digester, with the parameters of Table 5.1.
The electrical power of the ICE is 22.7 kW_{el}, the thermal power is 40.1 kW_{th}. During winter almost 90 % of the produced heat is needed to heat the digester. This is consistent with the affirmation of various farmers, who affirmed that it is usual to have no available heat during winter time. Furthermore, in summer there is an excess of heat production, which cannot always be used.

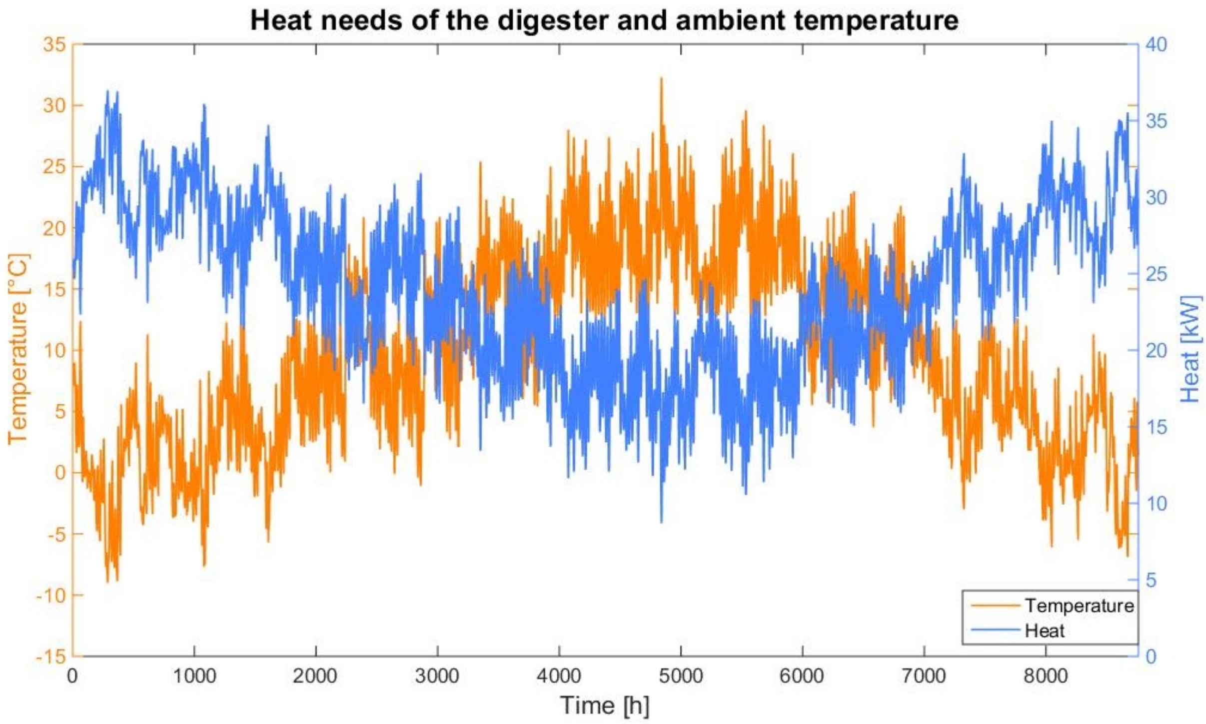


Figure 5.2: Heat needs of the digester and the ambient temperature

The parameters used and the most important results are indicated in the next table. The studied installation is an example of 8 farmers, of each 25 cows and 10ha, joining together to build a biogas installation.

Used parameters			
Electricity sources:	E_{source}	units	ICE
Electricity consumption:	E_{conso}	unit	digester
Heat source:	H_{source}	units	ICE
Heat consumption	H_{conso}	unit	digester
ICE capex:	$CAPEX_{ICE}$	$CHF \cdot kW^{-1}$	2,000
Biogas capex:	$CAPEX_{biogas}$	$CHF \cdot kW_{ch}^{-1}$	10,'000
ICE omex:	$OMEX_{ICE}$	$CHF \cdot kWh_{el}^{-1}$	0.025
Biogas omex:	$OMEX_{biogas}$	$CHF \cdot kW_{ch}^{-1}$	200
Feed-in tariff for the ICE (see chapter 2):	RPC_{ICE}	$CHF \cdot kWh^{-1}$	0.48
ICE lifetime:	LT_{ICE}	yr	10
Project lifetime:	$LT_{project}$	yr	20
ICE electrical efficiency:	$\varepsilon_{ICE\ elec}$	%	30
ICE thermal efficiency:	$\varepsilon_{ICE\ therm}$	%	53
Digester electrical needs of E_{biogas}:	$\varepsilon_{biogas\ elec}$	%	4.5
Digester thermal needs of E_{biogas}:	$\varepsilon_{biogas\ therm}$	%	31.8
Farm animals:		type	Dairy cow
Number of animals:		head count	200
Type of manure:		type	Liquid manure
Area of the farm:		ha	80
Results			
ICE size :	P_{ICE}	kW	22.7
Biogas size :	P_{biogas}	kW	75.8
ICE electricity production:	E_{ICE}	$kWh \cdot yr^{-1}$	169,327
ICE heat production:	H_{ICE}	$kWh \cdot yr^{-1}$	140,774
Total installation cost:	c_{tot}	$CHF \cdot yr^{-1}$	113,682
Total profits:	p_{tot}	$CHF \cdot yr^{-1}$	98,906
Total revenues (<0 is a profit):	r_{tot}	$CHF \cdot yr^{-1}$	14,775
Total savings on the heat:	p_{heat}	$CHF \cdot yr^{-1}$	17,630
Proportion of the savings to the profits:	$\pi_{savings}$	%	17.8
NPV of the project (<0 is profit):	NPV	CHF	219,821
Levellised electricity cost (ICE):	LEC_{ICE}	$CHF \cdot kWh^{-1}$	0.5672

Table 5.1: Parameters and results for the scenario N3 - ICE with biogas

The investment cost of the ICE is chosen low in this example. If it is increased to 4,000 CHF/kW$_{el}$, than the NPV becomes CHF 397,424 and the results are similar to those found in the report on Swiss biogas installation [17], showing that the values of the parameters are coherent. The main results of the report and of those found in Table 5.1 are summarised in the next table.

Results			
		Report [17]	Calculated
ICE size :	kW	25	22.7
ICE electricity production:	$kWh \cdot yr^{-1}$	170,000	169,327
ICE heat production:	$kWh \cdot yr^{-1}$	140,000	140,774
Total installation cost:	$CHF \cdot yr^{-1}$	122,540	125,620
Investment cost (CAPEX):	$CHF \cdot yr^{-1}$	60,000	69,549
Maintenance and operation cost (OMEX):	$CHF \cdot yr^{-1}$	52,040	41,509
Intermediate cultures cost (part of OMEX):	$CHF \cdot yr^{-1}$	11,500	8,882
Personnel cost (part of OMEX):	$CHF \cdot yr^{-1}$	7,280	7,280
Interest:	$CHF \cdot yr^{-1}$	10,500	14,561
Revenues (except from electricity sale):	$CHF \cdot yr^{-1}$	12,240	17,629
Levellised electricity cost (ICE):	$CHF \cdot kWh^{-1}$	0.6488	0.6378

Table 5.2: Results for the scenario N1 and comparison with the values of the report [17]

For the next calculation, the analysed farm, which is representative of the most common in Switzerland, consists of 20 cows with an area of 15 ha.
The investment cost of the ICE is fixed according to the actual market price of a small engine (6,000 CHF/kW$_{el}$, see chapter 3), with the electrical efficiency set as reported by the manufacturer (for NG). The used parameters and the results are described in the next table.

Used parameters			
Electricity sources:	E_{source}	units	ICE
Electricity consumption:	E_{conso}	unit	digester
Heat source:	H_{source}	units	ICE
Heat consumption	H_{conso}	unit	digester
ICE capex:	$CAPEX_{ICE}$	$CHF \cdot kW^{-1}$	6,000
Biogas capex:	$CAPEX_{biogas}$	$CHF \cdot kW_{ch}^{-1}$	10,000
ICE omex:	$OMEX_{ICE}$	$CHF \cdot kWh_{el}^{-1}$	0.025
Biogas omex:	$OMEX_{biogas}$	$CHF \cdot kW_{ch}^{-1}$	200
Feed-in tariff for the ICE (see chapter 2):	RPC_{ICE}	$CHF \cdot kWh^{-1}$	0.48
ICE lifetime:	LT_{ICE}	yr	10
Project lifetime:	$LT_{project}$	yr	20
ICE electrical efficiency:	$\varepsilon_{ICE\ elec}$	%	20
ICE thermal efficiency:	$\varepsilon_{ICE\ therm}$	%	70
Farm animals:		type	Dairy cow
Number of animals:		head count	20
Type of manure:		type	Liquid manure
Area of the farm:		ha	15
Results			
ICE size :	P_{ICE}	kW	1.87
Biogas size :	P_{biogas}	kW	9.36
ICE electricity production:	E_{ICE}	$kWh \cdot yr^{-1}$	12,712
ICE heat production:	H_{ICE}	$kWh \cdot yr^{-1}$	31,329
Total installation cost:	c_{tot}	$CHF \cdot yr^{-1}$	22,492
Total profits:	p_{tot}	$CHF \cdot yr^{-1}$	10,025
Total revenues (<0 is a profit):	r_{tot}	$CHF \cdot yr^{-1}$	12,467
Total savings on the heat:	p_{heat}	$CHF \cdot yr^{-1}$	3,923
Proportion of the savings to the profits:	$\pi_{savings}$	%	39
NPV of the project (<0 is profit):	NPV	CHF	185,480
Levellised electricity cost (ICE):	LEC_{ICE}	$CHF \cdot kWh^{-1}$	1.46

Table 5.3: Parameters and results for the scenario N1 - ICE with biogas

The LEC is 2.5 times higher than for an installation regrouping 8 farmers. The losses of building this facility are almost CHF 200,000.
If the investment cost of the biogas is reduced to 6,000 CHF/kW_{el} then the levellised electricity cost is reduced to 1.2 CHF/kWh_{el}. However, the NPV of the project is still positive (i.e. the project loses money).

Two additional calculations are performed in which the biogas investment cost is fixed at 8,000 and 6,000 CHF/kW_{ch}. The LECs are respectively 1.33 and 1.21 CHF/kWh_{el}, and the net present values are CHF 161,440 and CHF 137,410.
The low electrical efficiency and the high investment cost of small-size ICEs make them impossible to couple with biogas, even if the cost of the latter would drop drastically.

The size of the farm has a high impact on the biogas production. Increasing the number of the herd and the area of farm is beneficial to reduce some costs while increasing the profits (see Figure 5.3). In fact, it is common for farmers to associate together in order to set up a profitable biogas installation.

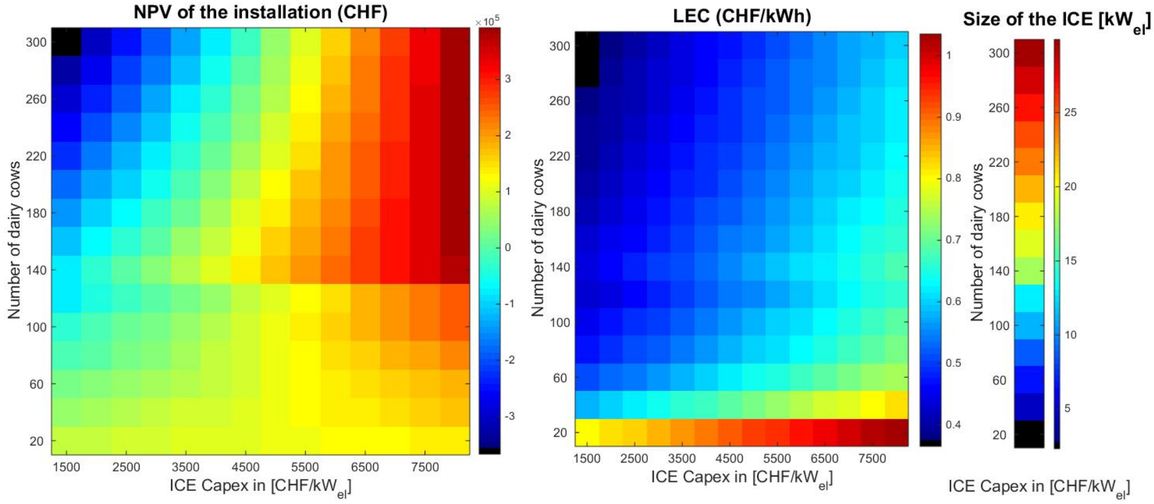


Figure 5.3: NPV of the installation and the levellised electricity cost - BIOGAS 6'000 CHF/kW$_{ch}$, elec. efficiency 20%

The project breaks even between the green and light blue colour. Seeing this figure, makes it clear that the investment cost of the engine is more important than the size of the herd until a certain value. When the latter is over 4,500 CHF/kW$_{el}$ then the project does not get profitable even with the largest analysed herd size. A small investment cost of 1,500 CHF/kW$_{el}$ for the ICE still needs 60 cows, three times over the average Swiss farm.

5.2 Scenario N2 - Farm with SOFC-biogas

The scenario N2 is the same as N1, only the ICE is replaced by a solid oxide fuel cell. The process flow is represented in Figure 5.1. The effect of some parameters will again be studied, as well as the investment cost of the fuel cell and of the biogas facility, the feed-in tariff, the electrical efficiency and the lifetime of the SOFC.

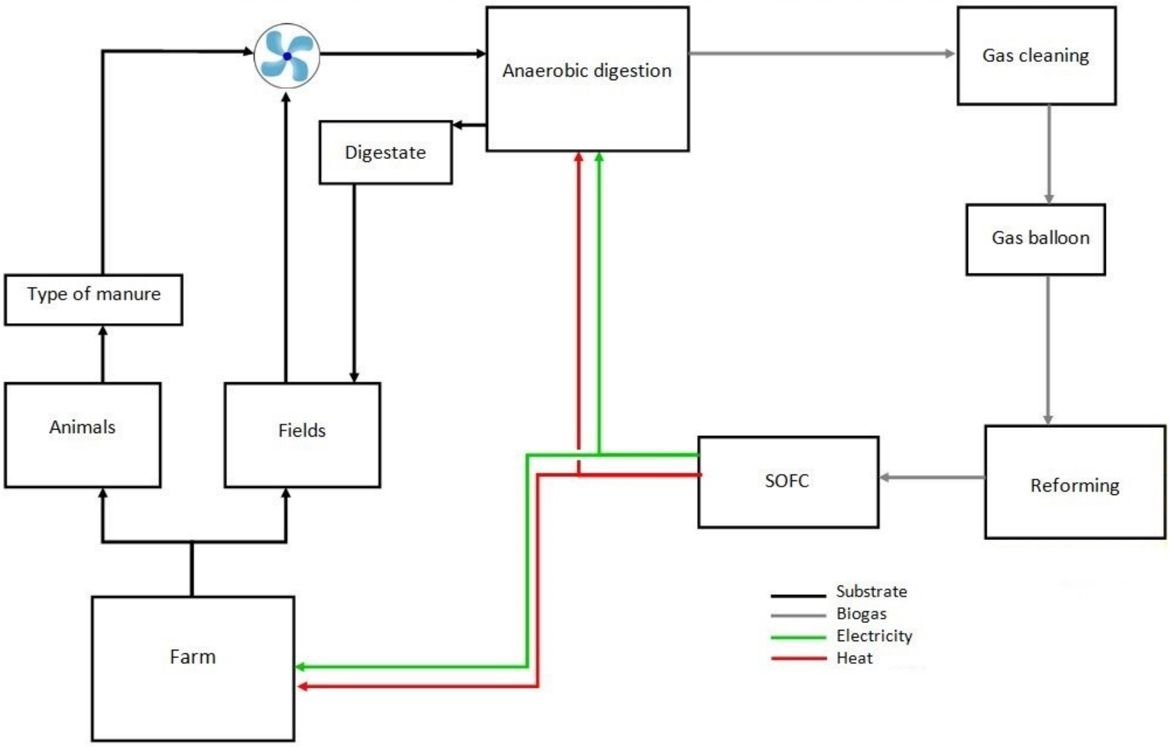


Figure 5.4: Schema of scenario N2 - see Figure 4.1 for the full schema

First of all, the reference scenario is taken for the calculation of the model. The price of the solid oxide fuel cell is fixed at 20,000 CHF/kW$_{el}$. The investment cost of the biogas facility the same as previously (10,000 CHF/kW$_{ch}$)

Used parameters			
Electricity sources:	E_{source}	units	SOFC
Electricity consumption:	E_{conso}	unit	digester
Heat source:	H_{source}	units	SOFC
Heat consumption	H_{conso}	unit	digester
SOFC capex:	$CAPEX_{SOFC}$	$CHF \cdot kW^{-1}$	20,000
Biogas capex:	$CAPEX_{biogas}$	$CHF \cdot kW_{ch}^{-1}$	10,000
SOFC omex:	$OMEX_{SOFC}$	$CHF \cdot kW_{el}^{-1}$	200
Biogas omex:	$OMEX_{biogas}$	$CHF \cdot kW_{ch}^{-1}$	200
Feed-in tariff for the ICE (see chapter 2):	RPC_{SOFC}	$CHF \cdot kWh^{-1}$	0.48
SOFC lifetime:	LT_{SOFC}	yr	10
Project lifetime:	$LT_{project}$	yr	20
SOFC electrical efficiency:	$\varepsilon_{SOFC\ elec}$	%	40
SOFC thermal efficiency:	$\varepsilon_{SOFC\ therm}$	%	40
Farm animals:		type	Dairy cow
Number of animals:		head count	20
Type of manure:		type	Liquid manure
Area of the farm:		ha	15
Results			
SOFC size :	P_{SOFC}	kW	3.75
Biogas size :	P_{biogas}	kW	9.36
SOFC electricity production:	E_{SOFC}	$kWh \cdot yr^{-1}$	29,114
SOFC heat production:	H_{SOFC}	$kWh \cdot yr^{-1}$	32,779
Total installation cost:	c_{tot}	$CHF \cdot yr^{-1}$	31,154
Total profits:	p_{tot}	$CHF \cdot yr^{-1}$	14,817
Total revenues (<0 is a profit):	r_{tot}	$CHF \cdot yr^{-1}$	16,337
Total savings on the heat:	p_{heat}	$CHF \cdot yr^{-1}$	842
Proportion of the savings to the profits:	$\pi_{savings}$	%	5.7
NPV of the project (<0 is profit):	NPV	CHF	243,050
Levellised electricity cost (SOFC):	LEC_{SOFC}	$CHF \cdot kWh^{-1}$	1.07

Table 5.4: Parameters and results for the scenario N2 - SOFC with biogas

With the most likely parameters, the combination SOFC-biogas is not profitable for an average Swiss farm as the project shows losses of CHF 230,000 .
On the other hand, the investment cost of the fuel cell is expected to drop in the next years. According to the manufactures and the learning curve of the technology, the price could drop as low as 4,000 CHF/kW$_{el}$.
The next figure studies the effect of the lifetime cost on the performance indicators.

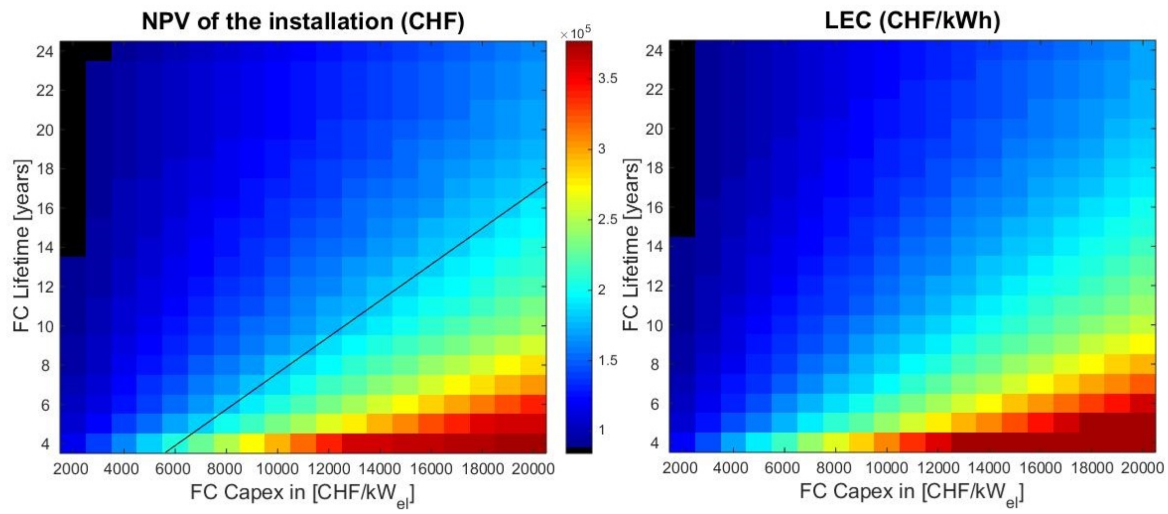


Figure 5.5: NPV of the installation and the levellised electricity cost in function of the lifetime and the investment cost of the SOFC - values of Table 5.4, black line: NPV=185,000

With the current prices of the biogas facility, the project will never be profitable. Even with a low investment cost of 2,000 CHF/kW$_{el}$ and a lifetime of 25 years of the SOFC, the LEC would be at

0.7 CHF/kWh$_{el}$ above the feed-in tariff of 0.48 CHF/kWh$_{el}$.
The fuel cell becomes more attractive than the ICE if the combination of the FC lifetime and investment cost is higher than the black line on Figure 5.5. The black line represents the NPV of the last scenario, which was CHF 185,480. A realistic SOFC which could compete with the ICE has a life expectancy of 10 years (or 87,600 h) with an investment cost of 13,000 CHF/kW$_{el}$.

An additional calculation is performed in which the biogas investment cost is fixed at 6,000 CHF/kW$_{ch}$ (see Figure 5.6).
The conditions of this project are still not profitable. However the LEC is at its lowest at 0.59 CHF/kW$_{el}$.

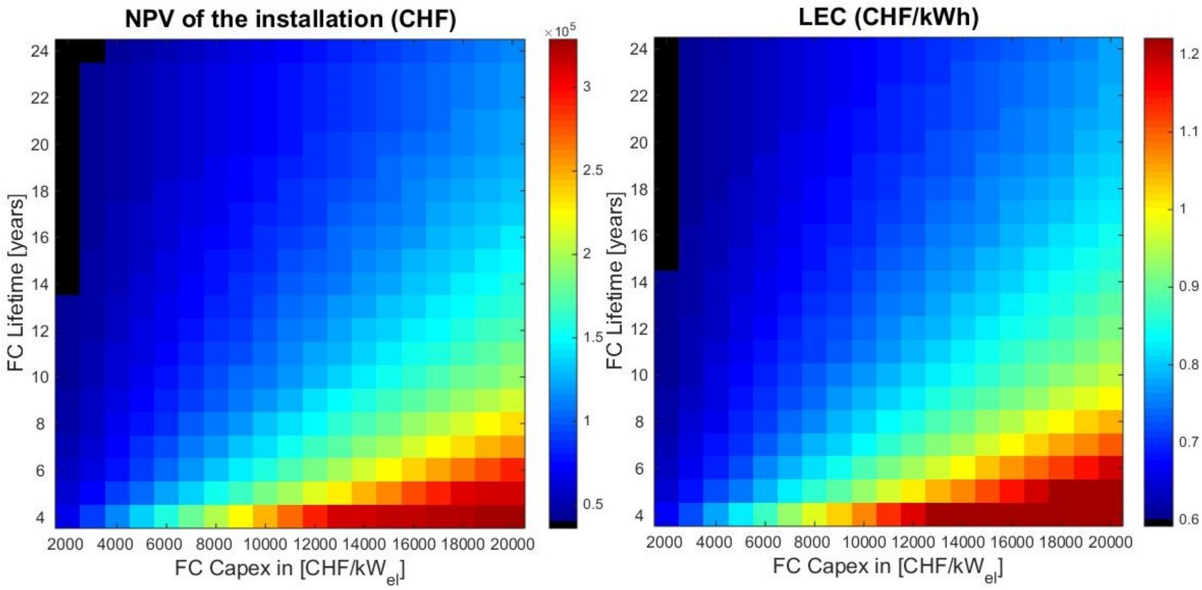


Figure 5.6: NPV of the installation and the levellised electricity cost in function of the lifetime and the investment cost of the SOFC - BIOGAS 6,000 CHF/kW$_{ch}$

The electrical efficiency of the SOFC needs to be increased to have an attractive project. In the next figure, the efficiency is augmented to 50%, which has been almost obtained in pilot plants running on biogas [97].
At around 5,500 CHF/kW$_{el}$ with a life-expectancy of 22 years, the SOFC fuelled on biogas will break even. The installation will still be profitable with a lifetime of 8 years, if the cost drops to 2,000 CHF/kW$_{el}$. The frontier of the profitability is marked with doted black lines.

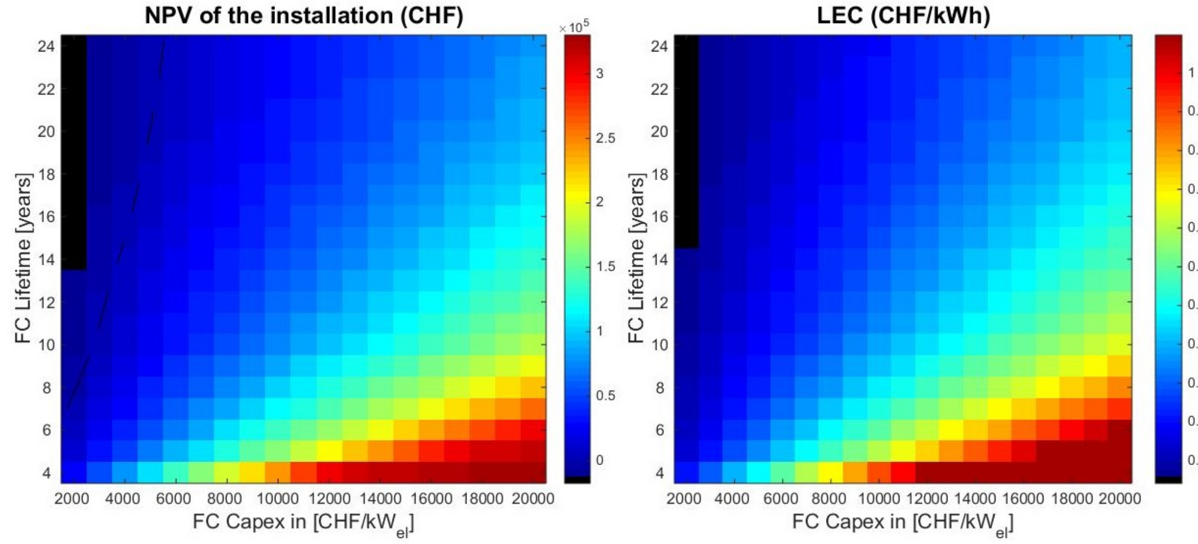


Figure 5.7: NPV of the installation and LEC in function of the lifetime and the investment cost of the SOFC - BIOGAS 6,000 CHF/kW$_{ch}$, elec. eff 50%, black line : NPV=0

These numbers seem difficult to reach, but the optimistic case with an high efficiency can be analysed for farms with a larger herd size. The case of a farm twice the size of the average one (40 dairy cows, 30 ha) is chosen, so as to still have a small-scale biogas plant.

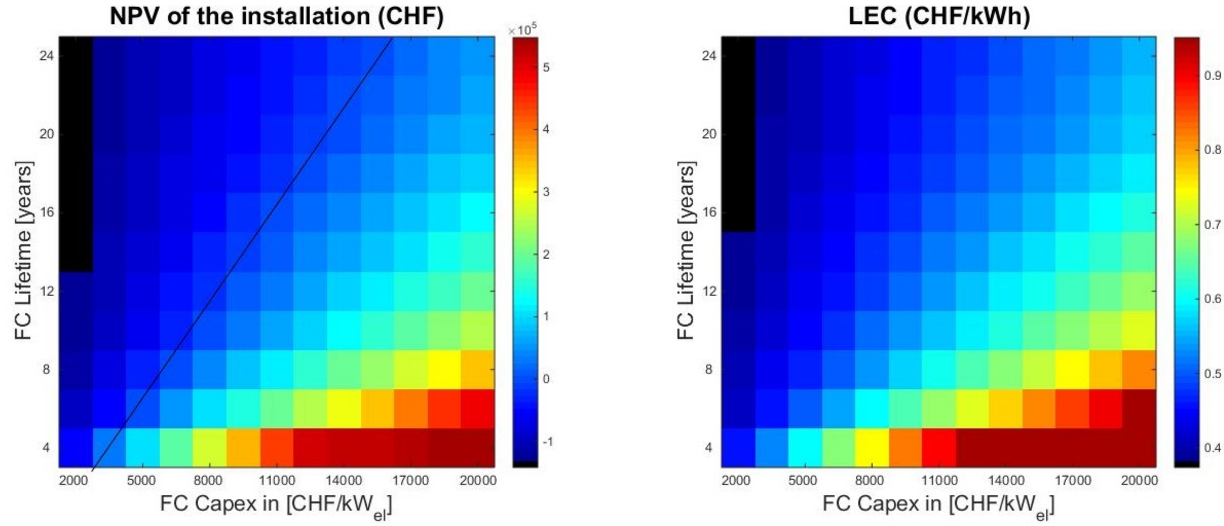


Figure 5.8: NPV of the installation and LEC in function of the LT and the investment cost of the SOFC - BIOGAS 6,000 CHF/kW$_{ch}$, elec. eff 50%, 40 dairy cows, black line is NPV=0

The size of the SOFC increased to 9.3 kW with 73,875 kWh of produced electricity. This installation is profitable for the combination: 8 years of life-expectancy and an investment cost of the SOFC of 5,000 CHF/kW$_{el}$;12 years with 8,000 CHF/kW$_{el}$, and 18 years with 12,500 CHF/kW$_{el}$. It is represented in Figure 5.8 by the black line.

5.3 Scenario N3 - Farm with SOFC-biogas-PV

In this scenario, the digester's electricity needs are either supplied by the solid oxide fuel cell or by an external renewable energy source. Only PV is considered here, coupled with a battery. The schema of the scenario is displayed in Figure 5.9.
In fact, heat could be supplied by solar thermal panels, but this doesn't make economic sense. As it can be seen in Figure 5.2, when the digester's heat needs are highest, the ambient temperature is at its lowest. Hence solar thermal panels would provide heat when none is needed (during summer) and would not be working when the demand is the highest (during winter).
A PV plant coupled with a battery can deliver a constant power to the digester, and if needed the SOFC would complete the electricity demand.

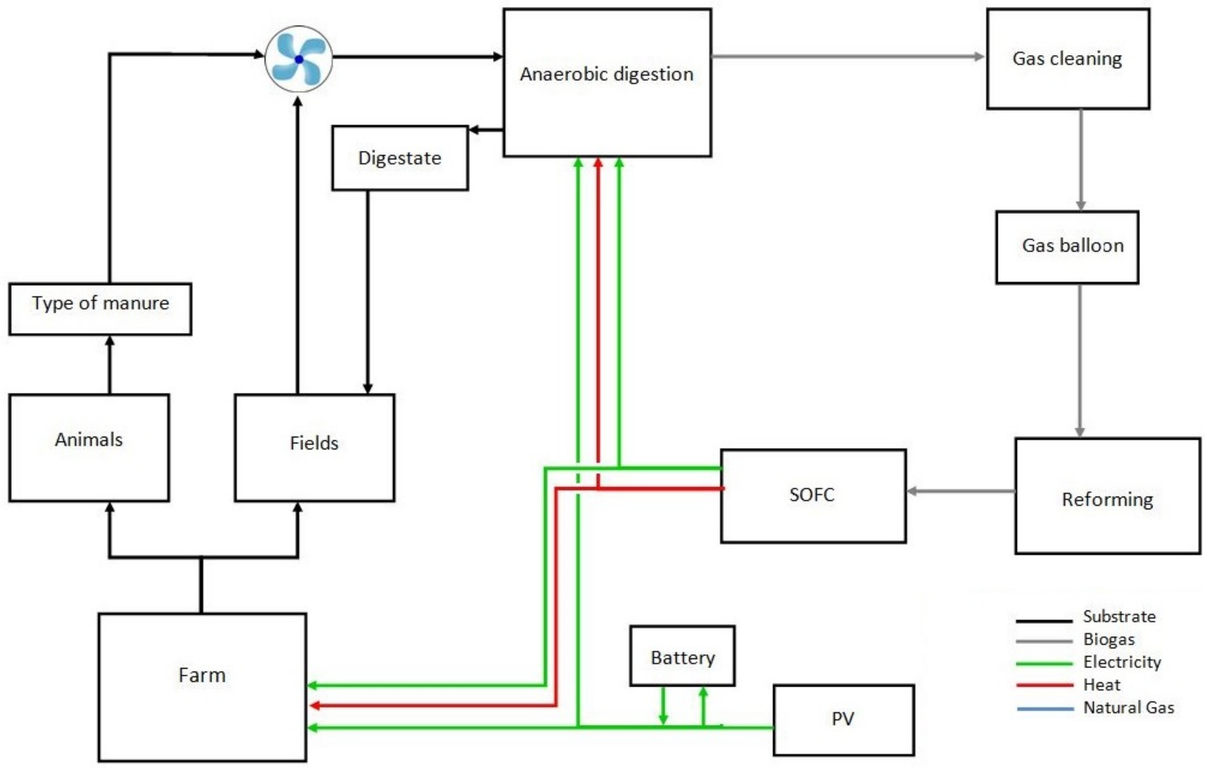


Figure 5.9: Schema of scenario N3 - see Figure 4.1 for the full schema

The size of the PV is related to the electrical efficiency of the digester. If the electricity needs are high (around 15%), then the PV plant should be larger. It should be kept in mind that all the produced electricity by the SOFC, fed in the digester, is not remunerated.
Therefore the performance indicators are analysed for various electrical efficiencies of the digester.

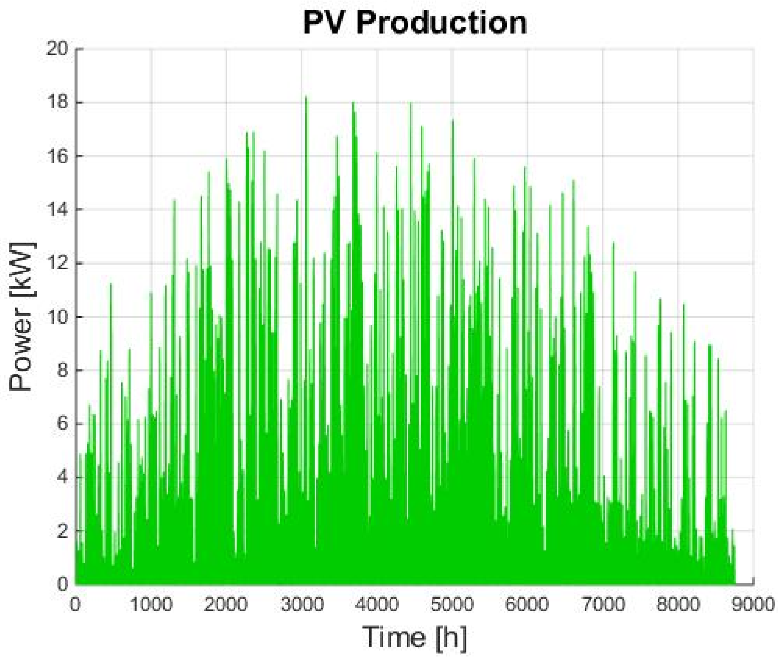


Figure 5.10: Production throughout the year of a PV installation in Ecublens (CH) [79]

The studied parameters are the investment cost of the PV, of the SOFC, and the electricity consumption of the installation.
The following figures represent the proportion of the digester's electricity needs which are provided by a PV installation. The solar panels can either supply electricity to the digester (through the battery) without direct remuneration or feed it in the electricity grid (without RPC at 8 cts/kWh) and cash in a proportional amount.

Table 5.5 presents the studied case, which will constitute a reference for the next figures.

Used parameters			
Electricity sources:	E_{source}	units	SOFC & PV
Electricity consumption:	E_{conso}	unit	digester
Heat source:	H_{source}	units	SOFC
Heat consumption	H_{conso}	unit	digester
SOFC capex:	$CAPEX_{SOFC}$	$CHF \cdot kW_{el}^{-1}$	20,000
Biogas capex:	$CAPEX_{biogas}$	$CHF \cdot kW_{ch}^{-1}$	10,000
PV capex:	$CAPEX_{PV}$	$CHF \cdot kW^{-1}$	2,500
Battery capex:	$CAPEX_{bat}$	$CHF \cdot kWh^{-1}$	1,000
SOFC omex:	$OMEX_{SOFC}$	$CHF \cdot kW_{el}^{-1}$	200
Biogas omex:	$OMEX_{biogas}$	$CHF \cdot kW_{ch}^{-1}$	200
PV omex:	$OMEX_{PV}$	$CHF \cdot kW^{-1}$	36
Battery capex:	$CAPEX_{bat}$	$CHF \cdot kWh^{-1}$	1,000
Feed-in tariff for the ICE (see chapter 2):	RPC_{SOFC}	$CHF \cdot kWh^{-1}$	0.48
Feed-in tariff for the PV (without contract):	fe_{PV}	$CHF \cdot kWh^{-1}$	0.08
SOFC lifetime:	LT_{SOFC}	yr	10
PV lifetime:	LT_{PV}	yr	25
Battery lifetime:	$LT_{battery}$	yr	9
Project lifetime:	$LT_{project}$	yr	20
SOFC electrical efficiency:	$\varepsilon_{SOFC\ elec}$	%	40
PV electrical efficiency:	$\varepsilon_{PV\ elec}$	%	16
SOFC thermal efficiency:	$\varepsilon_{SOFC\ therm}$	%	40
Farm animals:		type	Dairy cow
Number of animals:		head count	20
Type of manure:		type	Liquid manure
Area of the farm:		ha	15
Results			
SOFC size :	P_{SOFC}	kW	3.75
Biogas size :	P_{biogas}	kW	9.36
PV size :	P_{PV}	kW	3.66
Area of the roof needed for PV	S_{roof}	m^2	25.4
Battery size:	P_{bat}	kWh	7.9
SOFC electricity production:	E_{SOFC}	$kWh \cdot yr^{-1}$	31,949
PV electricity production:	E_{PV}	$kWh \cdot yr^{-1}$	4,630
PV electricity grid injection:	$E_{PV\ grid}$	$kWh \cdot yr^{-1}$	1,796
SOFC heat production:	H_{SOFC}	$kWh \cdot yr^{-1}$	32,779
Digester electricity consumption:	$E_{conso\ dig}$	kWh	3,691
Total installation cost:	c_{tot}	$CHF \cdot yr^{-1}$	32,017
Total profits:	p_{tot}	$CHF \cdot yr^{-1}$	16,312
Total revenues (<0 is a profit):	r_{tot}	$CHF \cdot yr^{-1}$	15,704
Total savings on the heat:	p_{heat}	$CHF \cdot yr^{-1}$	842
Proportion of the savings to the profits:	$\pi_{savings}$	%	5.2
Proportion of the digester electricity needs provided by PV:	$\pi_{dig\ PV}$	%	77
NPV of the project (<0 is profit):	NPV	CHF	233,640
Levellised electricity cost (SOFC):	LEC_{SOFC}	$CHF \cdot kWh^{-1}$	0.980

Table 5.5: Parameters and results for the scenario N3 - SOFC with biogas-PV

Moreover, it seems beneficial to install a PV plant, even with the current feed-in tariff. Around three quarters of the digester's electricity needs can be provided by a PV plant of 3.7 kW (needing a roof area of 26 m^2) coupled with a 8 kWh battery.

In order to produce a constant electricity supply from a PV plant, the battery needs to have a large capacity to provide current during the night. This means an important additional cost for the storage.
By choosing a PV plant which produces more electricity than the digester's needs, it will rely less on the storage and in that sense reduce the battery size and its related cost.
The profile of the electricity injection into the digester is presented for one week. The first figure reflects its use for a winter day, in which the PV will not produce enough electricity and the SOFC needs to supply most of the electricity (see Figure 5.11). The second figure represents the same process on a summer's day, in which the PV and the battery can supply alone the digester in electricity (see Figure 5.12).

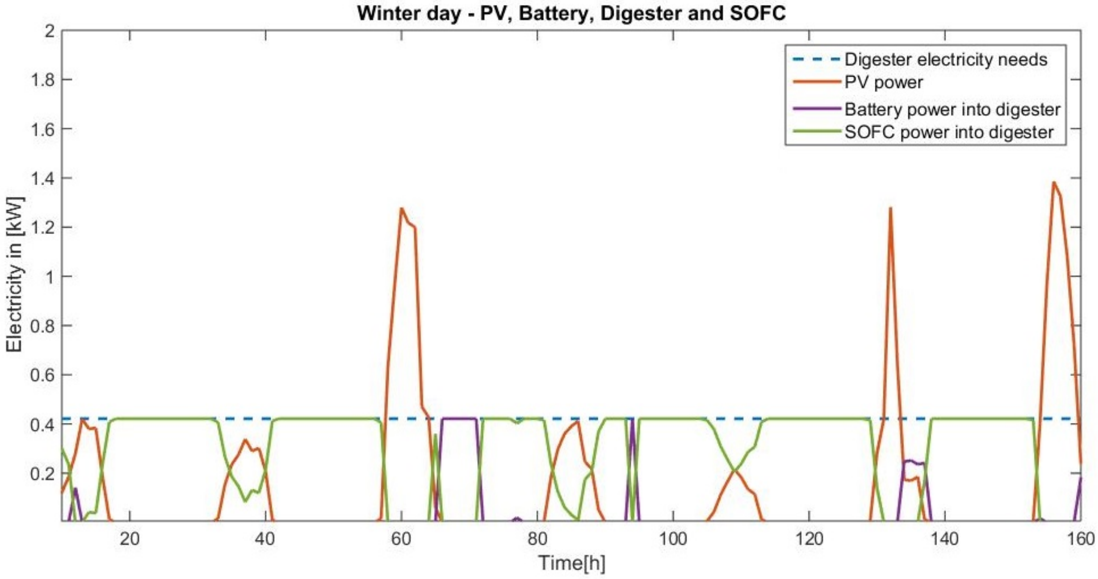


Figure 5.11: Production of the PV panels, digester electricity needs, and battery and SOFC electricity injection into the digester - winter day

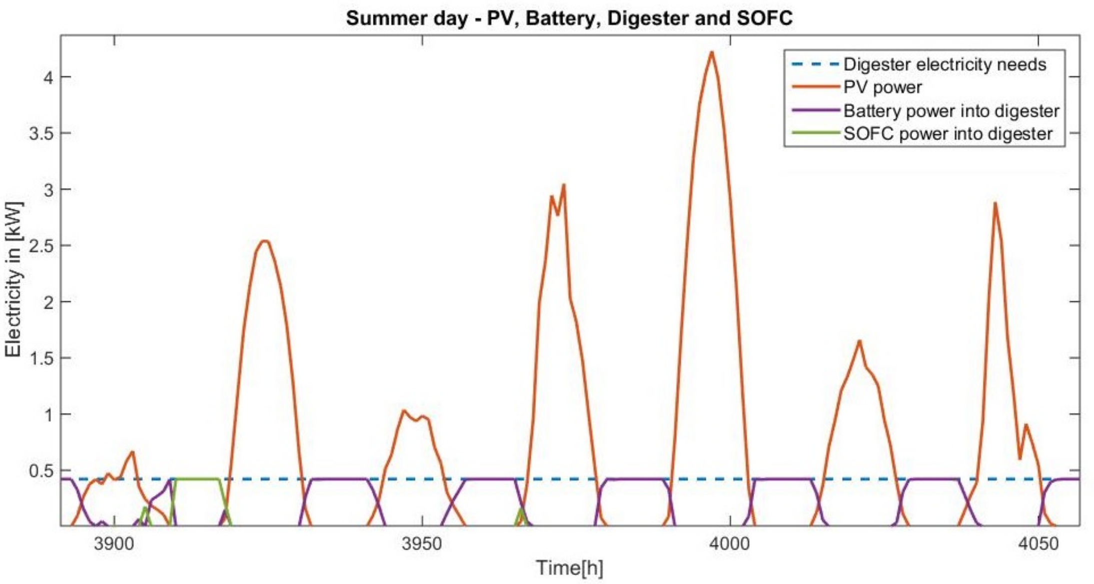


Figure 5.12: Production of the PV panels, digester electricity needs, and battery and SOFC electricity injection into the digester - summer day

More than two-thirds of the cost is needed for the biogas facility. The PV with the battery consists of less than 2% of the total costs while adding 9.2% more revenues than the last scenario (see Figure 5.13).

Moreover, as explained in chapter 2, the PV installation could be rewarded with a single contribution (RU) and this one-time revenue would decrease the cost by CHF 3,230 [121].

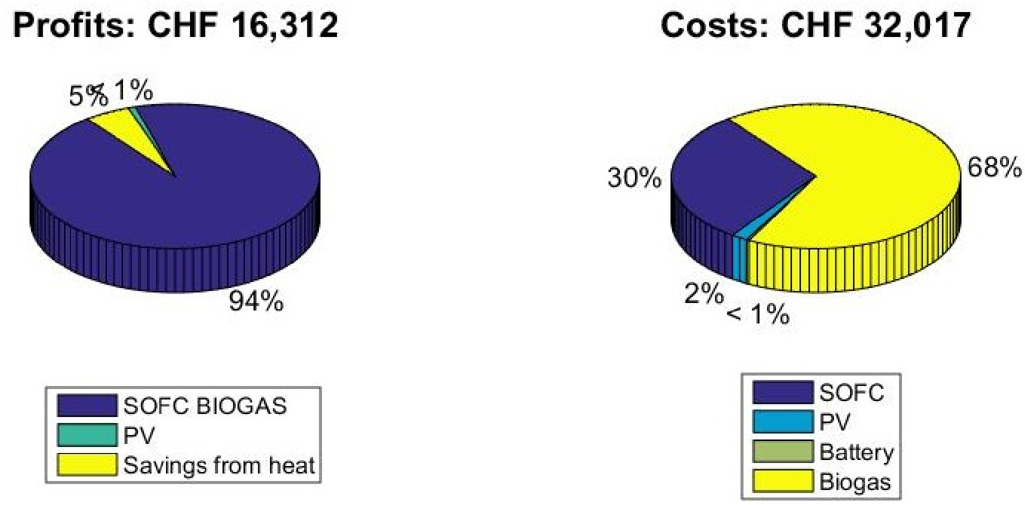


Figure 5.13: Division of the cost and the profits

The same analysis as previously is also done on this scenario. Profitability is not reached, but with a low biogas investment cost of 6.000 CHF/kW$_{ch}$ and a reasonable electrical efficiency of the SOFC (40%), the calculated LEC stays under 1 CHF/kWh$_{el}$.

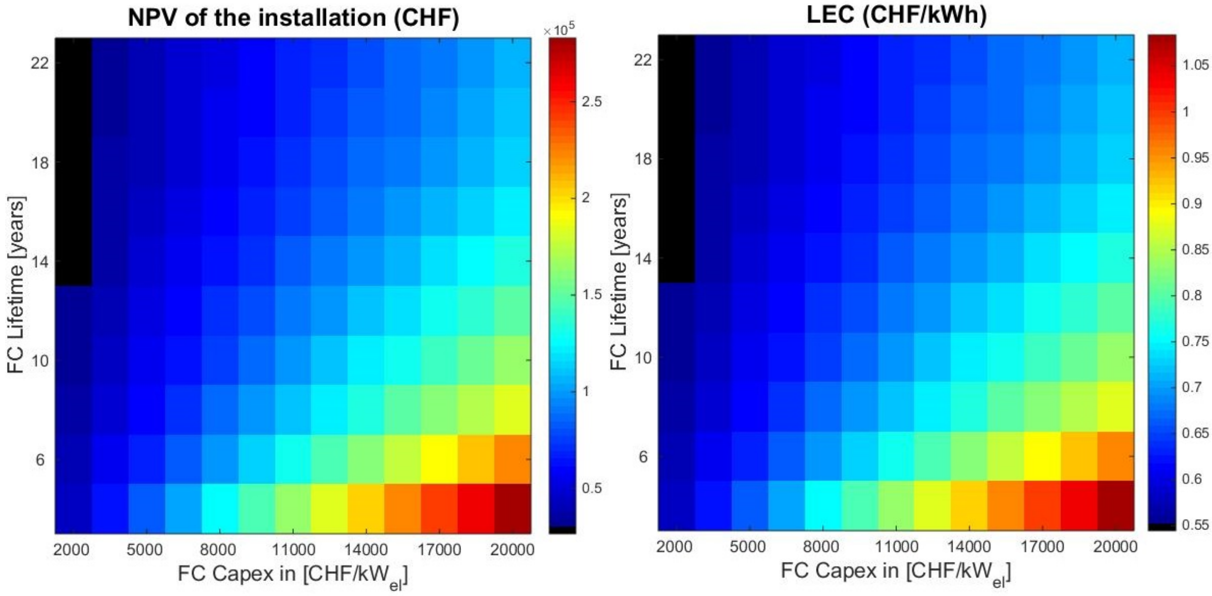


Figure 5.14: NPV of the installation and the levellised electricity cost in function of the lifetime and the investment cost of the SOFC - BIOGAS 6,000 CHF/kW$_{ch}$, elec. eff 40%

For a farm twice the size of the studied one, the installation is profitable if the investment cost of the SOFC is 8,000 CHF/kW$_{el}$ and the lifetime 10 years. Furthermore, the electrical efficiency needs to be 50% and the biogas cost, as before, 6,000 CHF/kW$_{ch}$. The black line on Figure 5.15 represents the zone where the NPV is zero. The expected lifetime needs to be over 12 years if the price of the SOFC does not decrease under 10,000 CHF/$_{el}$.

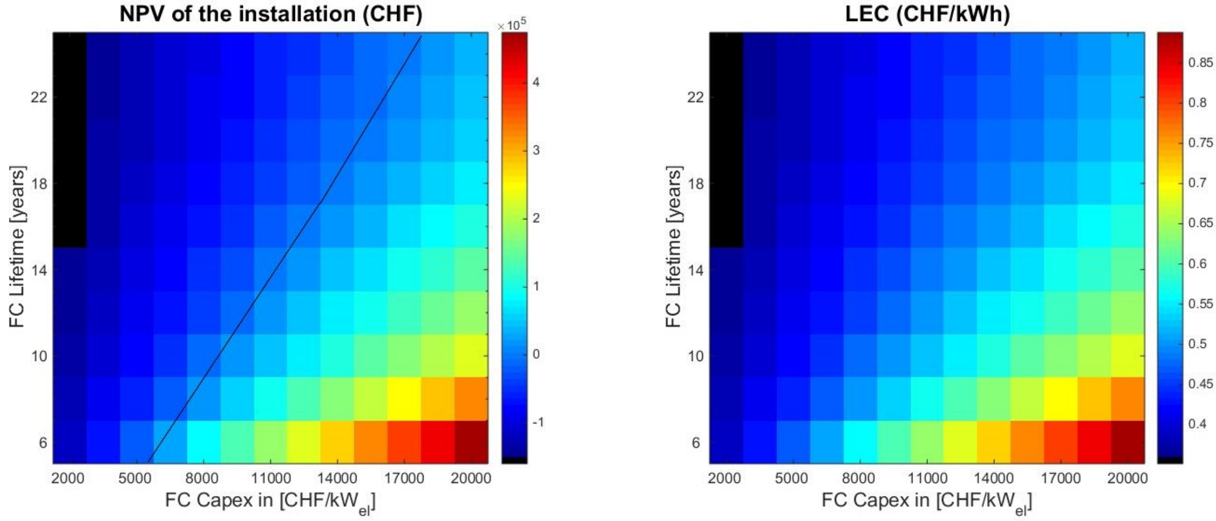


Figure 5.15: NPV of the installation and the LEC in function of the lifetime and the investment cost of the SOFC - BIOGAS 6,000 CHF/kW$_{ch}$, elec. eff 50%, 40 dairy cows, black line: NPV=0

5.4 Comparison of the scenarios

The three scenarios are compared to each other. Each one analyses the Swiss reference farm.
The divisions of the investment cost (see Figure 5.16) shows that a combustion engine is the cheapest of the three CHP combinations. The SOFC-PV scenario has the highest cost, but at the same time yields the most profits. In figures of energy output, the ICE produces the most heat, but less electricity than the fuel cell. The last scenario has the lowest levellised electricity cost of the three although this installation does not amount to any profit with the most realistic cost parameters. However, it is the most efficient and profitable solution of the three.
To make the biogas-SOFC facility attractive to a majority of Swiss farmers, the investment cost of the biogas installation needs to decrease to 6,000 CHF/kW$_{ch}$ and the SOFC electrical efficiency needs to increase to 50%. Furthermore, the SOFCs price has to diminish to 2,000 CHF/kW$_{el}$ with preferably an expected lifetime of 8 years.
For a farm of double the size (40 cows), the parameters become more favourable: a SOFC investment cost of 8,000 CHF/kW$_{el}$ and a life-expectancy of 12 years will make the project profitable (with ε_{SOFC}=50%).
The levellised electricity cost is the highest for the first scenario, but because less electricity is produced and the total cost is lower (see Figure 5.16) the net present value of this scenario is the lowest (i.e. less money is lost on this project).

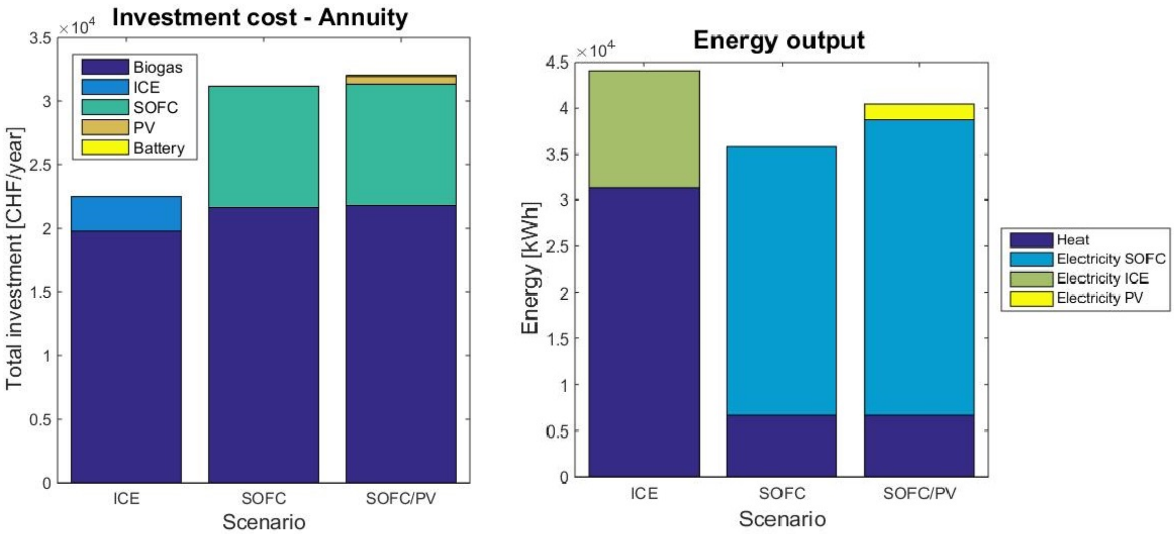


Figure 5.16: Comparison of the scenarios - Investment cost and Energy output

	NPV [CHF]	LEC [CHF/kWh]
Scenario 1	185,480	1.46
Scenario 2	243,050	1.07
Scenario 3	233,640	0.98

Table 5.6: Comparison of the scenarios - Performance indicators

6. Case study - Biogas from food waste at the EPFL

The case of equipping the EPFL and UNIL campuses with a digester and a SOFC is studied. The project is considered feasible from a technical and legal point as each year 228 tons of food waste are collected. It amounts to fuelling a SOFC in the range of 6.5 - 17.2 kW continuously on biogas, producing 50 - 147 MWh of electricity. The entire results are summarised in Table 6.7.

The EPFL has exactly 27 cafeterias and restaurants and 6 food-trucks, serving 8,041 students and 5,630 staff members, a total of 13,671 people (2014, [64]). The UNIL has 5 restaurants, for 14,165 students and 2,373 staff members, a total of 16,538. (2014,[65]). They sort their waste making it possible to collect the food left-overs. The FW is put in individual containers with a bar-code that allows the monitoring of each cafeteria. All the FW is sent to the farm de Saugealles, a biogas installation of 100kW which collects municipal and agricultural waste [66].

Valorising the food waste on site would create the first small-sized biogas plant on a Swiss campus coupled with a fuel cell. The project would reduce GHG emissions due to frequent transport of the FW with trucks. Furthermore, the SOFC is more efficient and emits less CO_2 than the CHP unit currently used in Saugealles [66].

The project is interesting as it could gather several laboratories of the EPFL around one facility: the laboratory for environmental biotechnology could study the biology of the digestion and develop methods to increase methane production while decreasing the creation of gaseous sulphur; the FUELMAT group could work on the purification of the biogas and on the performance enhancement of the FC; moreover, there are several other tasks which could be divided into different labs, such as the *in situ* monitoring of various gas components, the instrumentation of the FC, the electrical storage associated with the FC, the logistics around the facility, the analysis of the initial substrate and the digestate, the injection of the produced electricity into a local smart-grid and the analysis of its influence, the degradation of the FC stack due to harmful components [109]. To the knowledge of the author, no such plant[1] exists in Switzerland and no similar installation has been found worldwide. Some existing installations on university campuses are listed below, but the size difference is considerable and the CHP units are common ICE :

- University of California Davis : daily capacity of 50 tons of organic food waste (50% from UC Davis dining halls, animal facilities and grounds, 50% from food processing and distribution centers), yearly electricity production of 5.6 GWh, 500 kW. [70]
- Michigan State University South Campus : daily capacity of 40 tons (45.1% of manure, 25.6% of food processing waste, 25.6 % of fat,oils and greases (FOG) and 3.2 % of cafeteria FW which is 500 tons per year), yearly electricity production of 3 GWh, CHP of 400 kW, compost and liquid fertiliser are used on the campus and given to nearby farmers. [71]

[1]A small biogas installation (<20kW) on an university campus using only local waste coupled with a FC

- Swedish University of Agricultural Sciences, Lövsta: substrate is mainly manure and silage from the university's own operations and from neighbouring farms, yearly electricity production of 4 GWh, CHP 500 kW. [72]

The potential pilot plant on the EPFL campus would digest yearly 228 tons of FW and 3 tons of vegetable oil from both the EPFL and the UNIL.

In the next pages, the size and location of the potential biogas installation are presented, together with various aspects, such as the security and authorisations, the usage of the digestate and the production of food waste.

The current situation:
The city of Lausanne lends containers to the campus for a fee of CHF 60 per year and per container. The restaurants recycle their food wastes and the city comes to collect them, weighing the containers before taking them away. The collection fee is CHF 214 per ton. The vegetal oil is exempt from taxes and for a tariff of CHF 3, one container is cleaned[2]. Based on these values, an estimation of the yearly cost for both universities is done, which amounts to almost 60,000 CHF per year, with 83% for the collection fee.

The project was discussed with Prof. Holliger, an expert in anaerobic digestion [67], who raised some valid points over the feasibility of this idea.

First, the university campus will not provide a constant waste stream, with a expected decrease during the summer holidays. If the digester is continuously fed, this will be a problem because it costs a lot of money and time to stop the operation of a digester for a few weeks (i.e. the digester has to be emptied, bringing up the question where the content will be poured in; it is then cleaned, finally, for the start-up it needs micro-organisms to activate the decomposition process). Also the temperature of the digester can only rise of maximum 2 ℃ per day because of the presence of bacteria [32].

The second problem which arises is the utilisation of the digestate. Where will it be stored and where will it be used?

The solutions for the first problem could be to have a design of an installation with 2 digesters - using both when the university-life is at its highest, and only one during the holidays. This would solve the problem of where to store the content of the empty digester during the holidays: if the size is adequate, one digester will be emptied into the other, and after stopping for some time, some content of the working digester could be transferred into the second one in order to start the digestion process faster. Another way to stabilise the substrate's provision is to discuss with other partners and find suppliers, who are more active during the holidays. What comes to mind are nearby shops (Migro, Denner , Holy Cow..), as well as the grass which is being cut around that time. However, the two-digester solution is more viable than an unreliable substrate income. Finally, the problem of the usage of the digestate can be solved by getting into contact with local farmers, who could use this highly enriched natural fertiliser. In a circle of 9km diameter around the campus, more than 39 farmers have been found on a Swiss telephone book site (see Figure 6.1, [69]).

[2]if a company eliminates all their wastes through the sanitation service offered by the city, than the service is done for free.

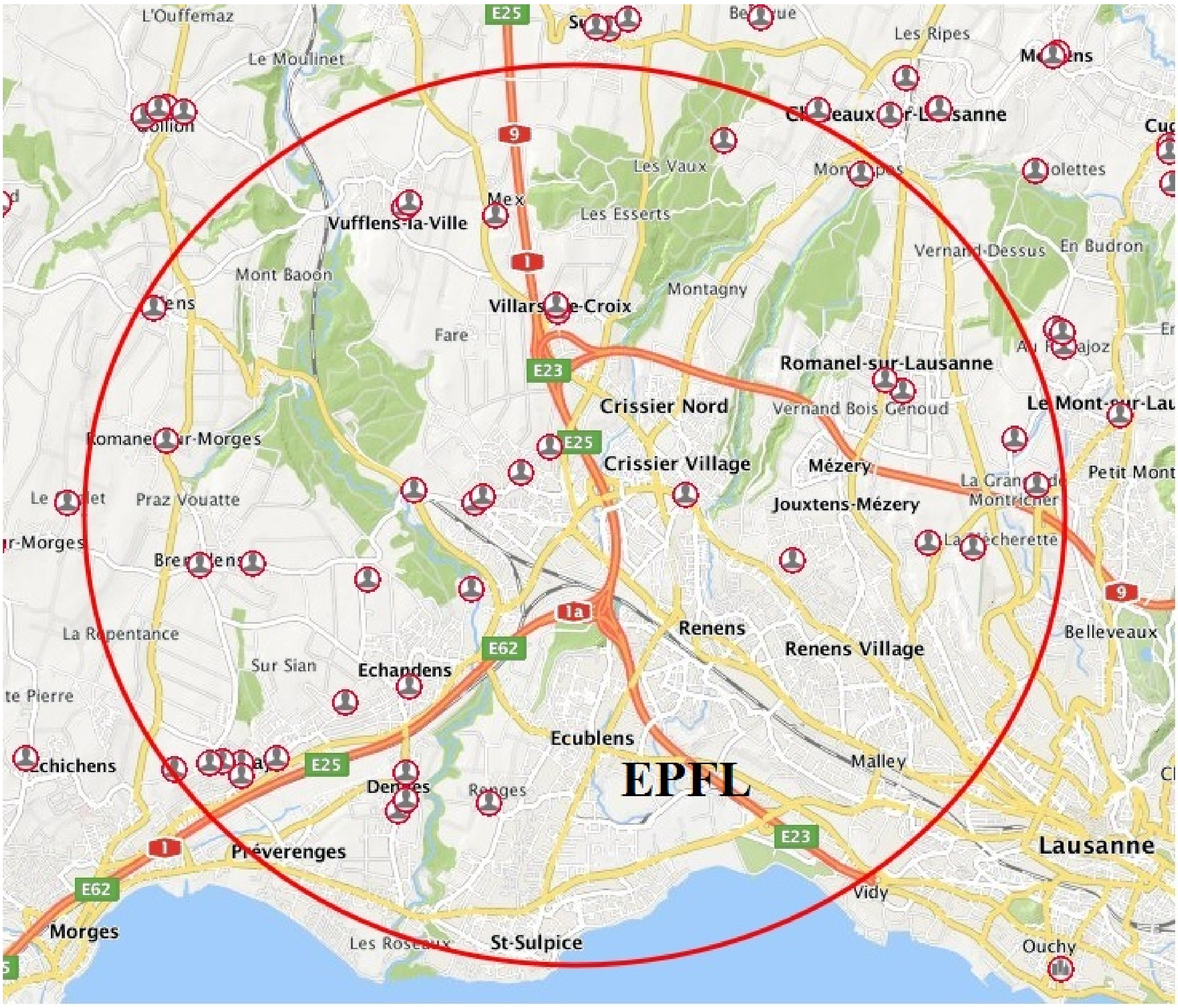


Figure 6.1: Area near the campus with all the agricultural sites represented with an icon, Circle of 9km diameter [69]

Another more innovative solution, would be to sell or to give the fertiliser in a liquid form to EPFL staff and students to use in their private garden. It could lead to future projects, like creating an open garden on the EPFL and UNIL campus and using the fertiliser in it.

Innovative solution for a biogas installation on the campus:
The feasibility of the project can only be studied with real data on the collected food waste. The City of Lausanne has a data-base with the weight of each container for each pick-up place and agreed to share the information (each container is equipped with a bar code for identification) [68].

In 2013, some participating restaurants or cafeterias of the EPFL shared a container. They are listed below:

- Vinci, Parmentier and 3 cafeterias,
- cafeteria of BC-INM,
- Le Corbusier,
- Rolex Learning Center,

- Le Copernic,
- L'Ornithorynque,
- Restaurant L'Epicure.

The UNIL also collect food waste and it is picked up for the same destination. It has been taken into account, as a participation of the UNIL in this project could be expected.

The UNIL had in 2014 four participating cafeterias/restaurants:

- Geopolis,
- FMEL,
- La Polychinelle,
- UNIL Banane.

In the next graph (Figure 6.2), the collected food waste of the EPFL and UNIL is represented for the consecutive years 2013-2014. Each point is a collection which occurs twice a week. The class period following the academic calender is marked with a green line.

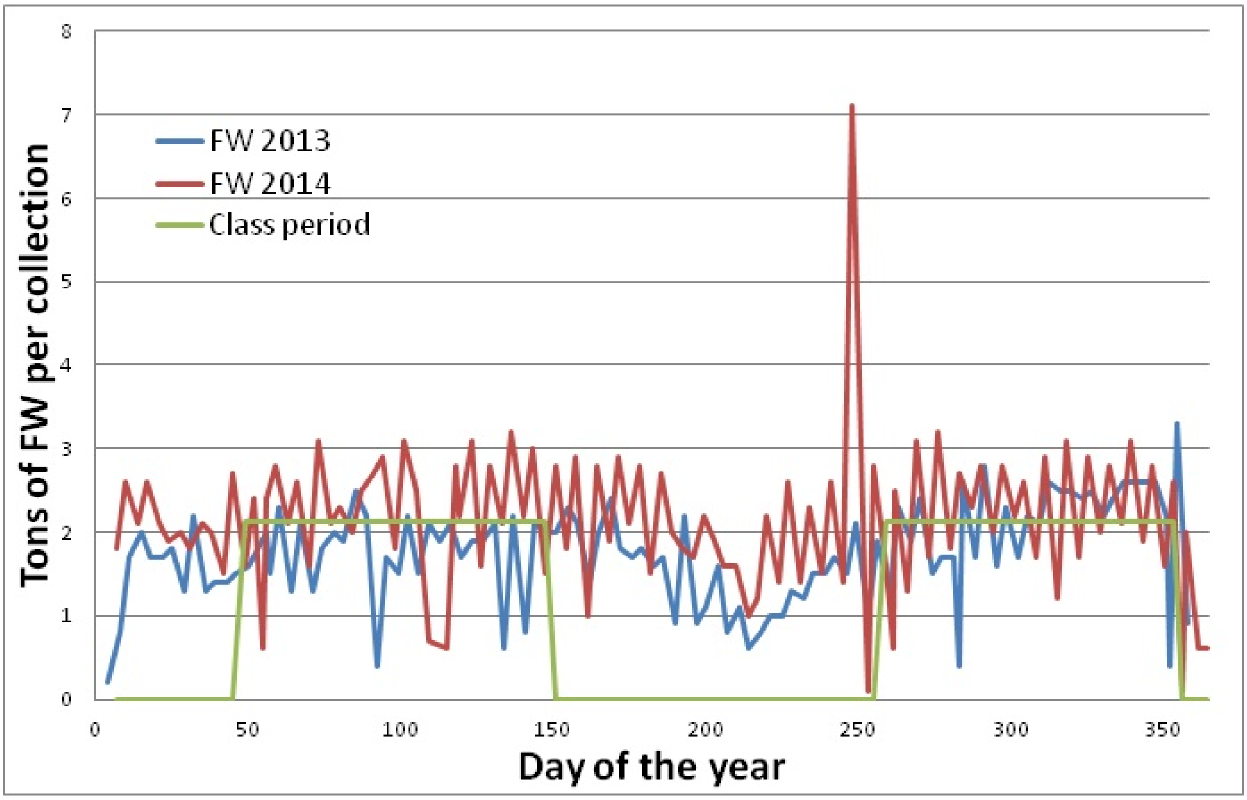


Figure 6.2: Food Waste collected from the EPFL-UNIL 2013-2014

In 2013, 181,2 tons of food waste have been sent to the biogas installation, of which the EPFL provides 43.9% (79.6 tons)of the total, with the UNIL sending the rest.

In 2014, the EPFL passed the UNIL's food waste production with 52.4% (119.4 tons)of the total collected FW, which amount to 228 tons. This is a growth of 25% compared to the previous year.

Surprisingly, the food waste collection on campus does not show a seasonal fluctuation. Even though the mass collected can vary strongly from one collection to the next, there is no clear decrease during the holiday period (see Figure 6.2).

To understand this fact, the EPFL's and UNIL's activity has to be considered. Even though there are only a few months of classes during the year, most of the students study and eat on campus during the preparation of the exams. Furthermore, there is a large number of steady paid workers on campus (43 % of the total campus' population): scientific, administrative and technical staff. Another fact is that the EPFL and UNIL propose various summer courses. All of this amounts to a constant activity of the restaurants and cafeterias throughout the year.

An analysis of the cumulative sum of the collected food waste gives an idea of the steadiness of the food waste collection. The two sums of the FW are plotted next to their corresponding linear function (see Figure 6.3). For 2013 and 2014, it is clear that their integral is almost linear, which means that there is no seasonal variation in the produced food waste. The year 2014 follows the line closer than the year before. The ramp of the two lines are the following: 0.51 and 0.63 for 2013 and 2014 respectively. The average daily food waste collection rose from 510 kg in 2013 to 630 kg in 2014.

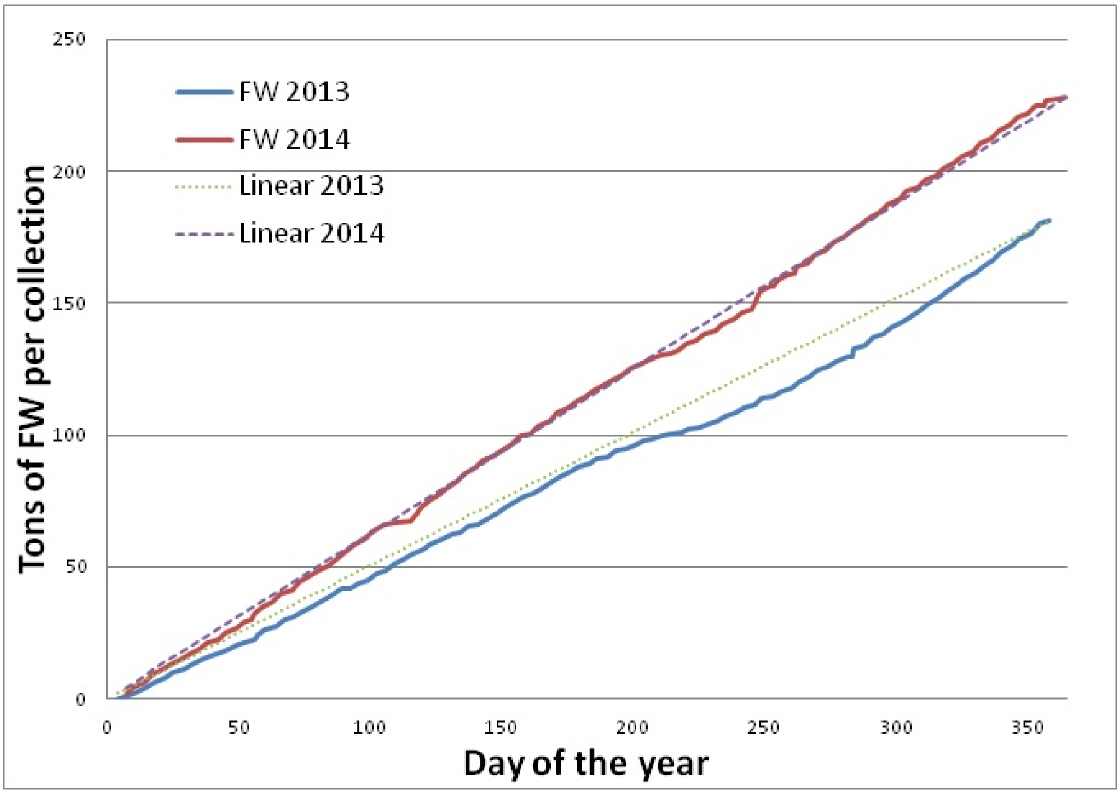


Figure 6.3: Food Waste collected from the EPFL-UNIL 2013-2014 - Summed up

On average, a pick-up at the campus is carried out each 3.37 days, with an average mass of 2.13 tons.

The collected food waste for each location on campus is presented in the next graph (Figure 6.4).

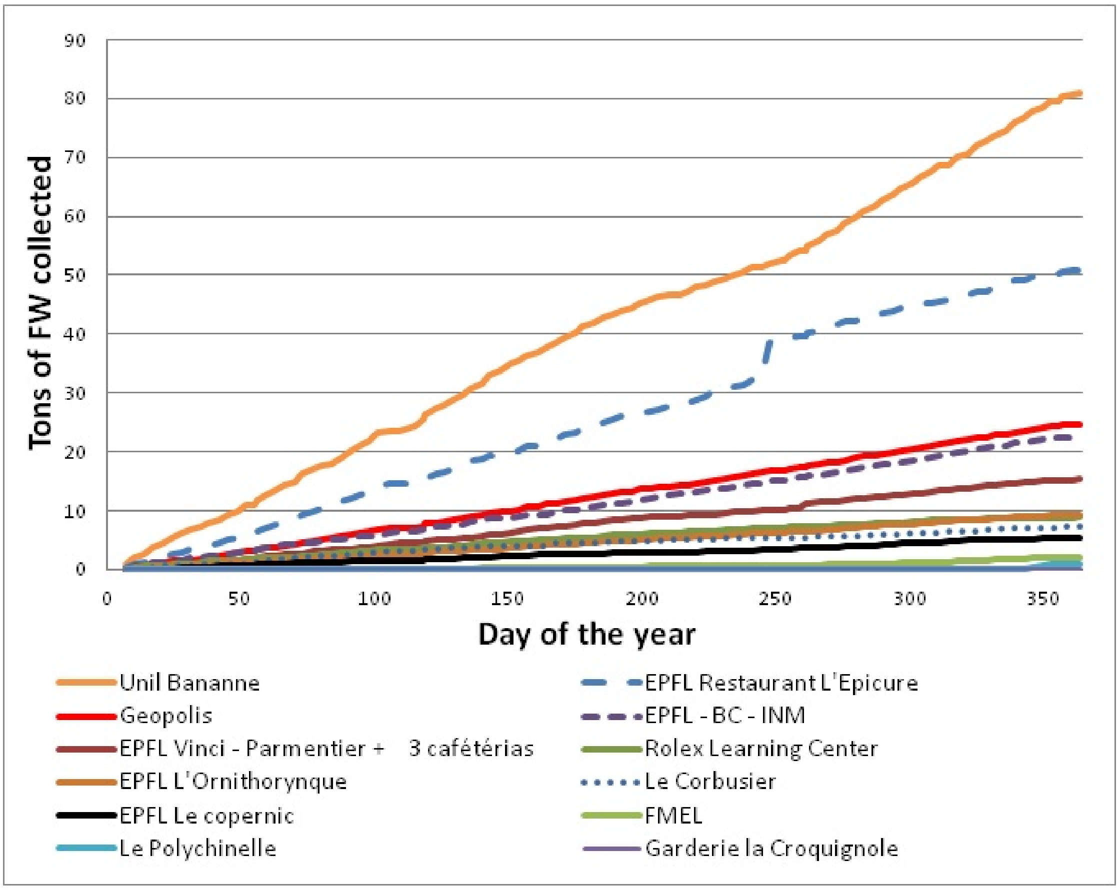


Figure 6.4: Food Waste collected from the EPFL-UNIL 2014 - Summed up for each location

The largest FW producer is the UNIL-Banane facility with 80.9 tons of FW in 2014. It is followed by the EPFL restaurant L'Epicure with 50.7 tons. Third and Fourth are the UNIL's Geopolis with 24.6 tons and the EPFL's cafeteria's BC-INM with 22.4 tons.

The EPFL's members, staff and students, have an average production of 8.73 kg FW per year, higher than the UNIL's member with 6.57 kg FW per year. This difference can be explained both with the staff member population of the EPFL, which is 2.4 times higher than the UNIL's and with the difference in the number of restaurants. Unlike the students, the staff members eat on campus on a daily basis throughout the year. Assuming 52 weeks per year, and 5 opening days per week (even if some cafeterias open on Saturdays), the campus restaurants and dinner halls would be open for 261 days a year. This would mean an average per *working* day of 874 kg. Every EPFL and UNIL member produced 33.4 and 25.2 g of FW per *working* day in 2014.

Finally, the size of the digester is studied, likewise the quantity of produced biogas, the volume of digestate, the commercialised biogas production equipment which could be installed, the cost of this project and the concerns connected with the installation.

Digester size:
The size of the digester is estimated by setting a retention time. In section 1.1.1, Figure 1.3 showed that FW has the highest yield, if it is set at 30 days.

In Figure 6.3, the curve of the FW of 2014 is under the linear function (except for a brief time at the end of the year 2014), meaning that by estimating a collected mass of 2.131 t of FW with a frequency of 3.368 days, the real collected mass will always be under this estimate. For a retention time of 30 days, the digester will have to contain:

$$\frac{\mathrm{m}_{\text{FW per collec}}}{f_{collection}} \cdot T_{retention} \Rightarrow \frac{2.131 \cdot 10^3[\mathrm{kg}]}{3.368[\mathrm{d}]} \cdot 30[\mathrm{d}] = 0.633 \cdot 10^3[\frac{\mathrm{kg}}{\mathrm{d}}] \cdot 30[\mathrm{d}] = 19.0 \cdot 10^3[\mathrm{kg}] \tag{6.1}$$

A choice is made here concerning the considered mass intake: The current situation of 633 kg per day will not be sufficient for the next years. The campus population has been increasing drastically for years. However, this growth will be less spectacular, as the direction is trying to take measures to bring it to a constant. Additionally, the recycling rate may increase as people become more aware of the benefits of recycling.

It has been chosen to take a 30 % bigger mass intake in order to cover the needs of the next years. If one digester should not be enough then a second one could be installed in parallel.

$$\mathrm{m}_{\text{digester}} \cdot 130\% \Rightarrow 19.0 \cdot 10^3[\mathrm{kg}] \cdot 130\% = 24.7 \cdot 10^3[\mathrm{kg}] \tag{6.2}$$

When considering the size of a digester, it is necessary to consider a limit in the volume: the digester can only be filled up to 80% of its volume as this is to prevent overfills and be able to deal with daily variations. There is no difference if the volume or the mass is increased, as they are proportional through the mass density.

The final digester capacity will be 1/4 higher (125%=1/80%):

$$\mathrm{m}_{\text{digester}} \cdot 125\% \Rightarrow 24.7 \cdot 10^3[\mathrm{kg}] \cdot 125\% = 30.8 \cdot 10^3[\mathrm{kg}] \tag{6.3}$$

The volume of the digester is calculated using the average density of the food waste, which can be estimated to be around 850-1'000 kg/Nm^3 [133].

$$\begin{aligned} \mathrm{V}_{\text{digester max}} &= \mathrm{m}_{\text{digester}}/\rho_{\text{FW min}} \Rightarrow \frac{30.8 \cdot 10^3[\mathrm{kg}]}{850[\mathrm{kg/Nm^3}]} = 36.3[\mathrm{Nm^3}] \\ \mathrm{V}_{\text{digester min}} &= \mathrm{m}_{\text{digester}}/\rho_{\text{FW max}} \Rightarrow \frac{30.8 \cdot 10^3[\mathrm{kg}]}{1'000[\mathrm{kg/Nm^3}]} = 30.8[\mathrm{Nm^3}] \end{aligned} \tag{6.4}$$

Another important aspect is the digestate storage, which needs to be dimensioned. The only mass flow which enters the digester is the FW ($\dot{\mathrm{m}}_{FW}$), the two leaving are the biogas ($\dot{\mathrm{m}}_{biogas}$) and the digestate ($\dot{\mathrm{m}}_{digestate}$). The mass balance is thus:

$$\dot{m}_{FW} = \dot{\mathrm{m}}_{\text{biogas}} + \dot{\mathrm{m}}_{\text{digestate}} \tag{6.5}$$

The weight of biogas is calculated using:

$$\dot{m}_{biogas} = \dot{\mathrm{V}}_{\text{biogas}} \cdot \rho_{\text{biogas}} \tag{6.6}$$

The volume of biogas derived from FW is calculated using the biogas yield and density. The value of the biogas yield is taken from Table A.9 in Annex A, by taking the average value. The density is considered constant at 1.1 [kg/Nm^3][168] [167].

$$V_{biogas} = 200[\frac{\mathrm{m^3}}{\mathrm{t}_{\text{wet weight FW}}}] \tag{6.7}$$

and

$$\rho_{biogas} = 1.1[\frac{\mathrm{kg}}{\mathrm{Nm^3}}] \tag{6.8}$$

Using equations 6.2, 6.5, 6.6, 6.7 and 6.8, the mass flow of digestate is [3]:

$$\begin{aligned}
&\dot{m}_{digestate} = \dot{\mathrm{m}}_{\mathrm{FW}} - \dot{\mathrm{m}}_{\mathrm{biogas}} \\
\Leftrightarrow\ &\dot{m}_{digestate} = \dot{\mathrm{m}}_{\mathrm{FW}} - \dot{\mathrm{V}}_{\mathrm{biogas}} \cdot \rho_{\mathrm{biogas}} \\
\Leftrightarrow\ &\dot{m}_{digestate} = \dot{\mathrm{m}}_{\mathrm{FW}} - \mathrm{V}_{\mathrm{biogas}} \cdot \dot{\mathrm{m}}_{\mathrm{FW}} \cdot \rho_{\mathrm{biogas}} \\
\Leftrightarrow\ &\dot{m}_{digestate} = \dot{\mathrm{m}}_{\mathrm{FW}} \cdot (1 - \mathrm{V}_{\mathrm{biogas}} \cdot \rho_{\mathrm{biogas}}) \\
\Leftrightarrow\ &\dot{m}_{digestate} = 24.7 \cdot 10^3 [\frac{\mathrm{kg}}{30\ \mathrm{days}}](1 - 200[\frac{\mathrm{m}^3}{\mathrm{t}_{\mathrm{wet\ weight\ FW}}}] \cdot 1.1[\frac{\mathrm{kg}}{\mathrm{Nm}^3}]) \\
\Leftrightarrow\ &\dot{m}_{digestate} = 19.3 \cdot 10^3 [\frac{\mathrm{kg}}{30\ \mathrm{days}}]
\end{aligned} \tag{6.9}$$

and the mass flow of biogas:

$$\begin{aligned}
&\dot{m}_{biogas} = \dot{\mathrm{m}}_{\mathrm{FW}} - \dot{\mathrm{m}}_{\mathrm{digestate}} \\
\Leftrightarrow\ &\dot{m}_{biogas} = 24.7 \cdot 10^3 [\frac{\mathrm{kg}}{30\ \mathrm{days}}] - 19.3 \cdot 10^3 [\frac{\mathrm{kg}}{30\ \mathrm{days}}] \\
\Leftrightarrow\ &\dot{m}_{biogas} = 5.4 \cdot 10^3 [\frac{\mathrm{kg}}{30\ \mathrm{days}}]
\end{aligned} \tag{6.10}$$

The density of the digested food waste (DFW) needs to be found to dimension the storage pit. In Annex A a precise method for determining the DFW's density is presented. The required parameters are the initial components (crude protein, crude fat, crude fibre, crude ash, nitrogen-free extract (Nfe[4]) of the FW and the storage temperature. However, as they are not known an approximation is necessary at this point (see Table 6.1).

Component	Density [kg/m^3]	
	min	max
FW	850	1'000
DFW	750	1'100

Table 6.1: Estimation of the density of FW and DFW

The volume of the storage pit can be finally estimated:

$$\begin{aligned}
&\mathrm{V}_{\mathrm{digestate}} = m_{digestate}/\rho_{digestate} \\
&\mathrm{V}_{\mathrm{digestate}} = 19.3 \cdot 10^3 [\mathrm{kg}]/\rho_{digestate}[\mathrm{kg/m}^3]
\end{aligned} \tag{6.11}$$

with $m_{digestate}$ being the amount of DFW produced after a retention time of 30 days.

The current Swiss regulation [128] requires the digestate to be stored for 5 months in plain territory and 6 months in mountainous areas. The storage pit for the liquid DFW will be:

$$\begin{aligned}
&\mathrm{V}_{\mathrm{digestate\ storage}} = V_{digestate} \cdot 5[months] \\
\Leftrightarrow\ &\begin{cases} \mathrm{V}_{\mathrm{digestate\ storage\ min}} = 19.3 \cdot 10^3 [\mathrm{kg}]/\rho_{digestate\ max} \cdot 5[months] \\ \mathrm{V}_{\mathrm{digestate\ storage\ max}} = 19.3 \cdot 10^3 [\mathrm{kg}]/\rho_{digestate\ min} \cdot 5[months] \end{cases} \\
\Leftrightarrow\ &\begin{cases} \mathrm{V}_{\mathrm{digestate\ storage\ min}} = 17.5[\mathrm{m}^3] \cdot 5[months] \\ \mathrm{V}_{\mathrm{digestate\ storage\ max}} = 25.7[\mathrm{m}^3] \cdot 5[months] \end{cases} \\
\Leftrightarrow\ &\begin{cases} \mathrm{V}_{\mathrm{digestate\ storage\ min}} = 88[\mathrm{m}^3] \\ \mathrm{V}_{\mathrm{digestate\ storage\ max}} = 129[\mathrm{m}^3] \end{cases}
\end{aligned} \tag{6.12}$$

[3] These values are with the estimated 30% increase in FW collection

[4] Nfe consists of the sugars and starches, it is what is left after water, ash, fiber, crude protein and fat have been removed

Nevertheless, it is possible to reduce the size of the DFW pit by different means: first the digestate can be separated into a solid and a liquid phase. The solid phase can be transported to a nearby compost and the liquid phase will have to be stored on the spot, which will reduce the volume and the mass of the liquid digestate. Furthermore, the 5 months storage period is for an agricultural site and could be smaller for this project and considering the location of the installation, it could be conceivable to transport each month the DFW to another biogas facility, where it could be used in the digestion process or be stored in their pits. The monthly produced volume is similar to a tank-truck's, thus only needing 12 trips per year.

Biogas potential and SOFC size:
The biogas potential is quickly calculated knowing the total yearly collected volume of FW and of vegetable oil.

$$\begin{aligned} \mathrm{E_{ch\,FW\,biogas}} &= m_{FW} \cdot 10^3 \cdot Y_{FW\,VS\,CH4} \cdot VS_{FW} \cdot Y_{CH4} \\ \mathrm{E_{ch\,oil\,biogas}} &= m_{oil} \cdot 10^3 \cdot Y_{oil\,VS\,CH4} \cdot VS_{oil} \cdot Y_{CH4} \\ \mathrm{E_{ch\,total\,biogas}} &= \mathrm{E_{ch\,FW\,biogas}} + \mathrm{E_{ch\,oil\,biogas}} \end{aligned} \tag{6.13}$$

with $E_{ch\,FW\,biogas}$ the chemical energy of the FW's biogas [kWh] (or vegetable oil), m_{FW} the total FW collected in 2014 [t] (or oil), $Y_{FW\,VS\,CH4}$ the methane yield of FW (or oil) per VS [$\mathrm{m^3_{CH_4} \cdot kg^{-1}_{VS}}$], VS_{FW} the VS in proportion of wet FW mass and Y_{CH4} the methane energy density.
All the used parameters are described in Table 6.7.

The parameter $Y_{FW\,VS\,CH4}$ is highly dependent on the FW quality. It is very difficult to make a guess as to its value as no measurements have been done on campus' FW. In this regard, the specialised literature has been consulted and all the values for cafeteria food waste have been collected (the results are presented in Annex A in Table A.9). The extreme values have been kept and are used to estimate the smallest and the highest potential (see Table 6.2). Furthermore the VS content in FW (VS_{FW}) needs to be estimated. The same principle has also been applied here, but as the values do not differ too much, the most common value has been taken for the calculations. Not a lot of data has been found on the value of $Y_{oil\,CH4}$, but vegetable oil is not as variant as FW.

Component	Methane Yield per VS: $Y_{VS\,CH4}$ [$\mathrm{m^3_{CH_4} \cdot kg^{-1}_{VS}}$]	
	min	max
FW	0.3	0.6
Component	VS content [% of wet mass]	
	used value	
FW	20	
Oil	84	
Component	Methane Yield per wet mass :Y_{CH4} [$\mathrm{m^3_{CH_4} \cdot kg^{-1}_{wet\ mass}}$]	
	min	max
FW	0.06	0.12
Oil	0.79	

Table 6.2: Estimation of the FW biogas' potential

Using equation 6.13 and the Table 6.2, the smallest and highest estimation are calculated. They are presented below:

Component	Chemical energy [MWh/yr]	
	min	max
FW	138	277
oil	24	
Total	162	301

Table 6.3: Estimation of the biogas energy

Depending on the estimation, the total biogas potential lies at 162 or 301 MWh.
A last estimation on the SOFC electrical efficiency is done in order to estimate the real electricity production.
From what has been found in the literature, an efficiency of 35% is very easily reached on the whole system (even though stack efficiencies can reach up to 75%). With a bit of know-how and optimisation (which the EPFL has), the system electrical efficiency could reach 50%. In order to avoid approximations, both values are taken for the maximum and minimum. Assuming a continuous operation throughout the year, the power and the electrical production of the SOFC are estimated:

Efficiency[%]	Produced electricity [MWh/yr]	
	min	max
35	56.8	105.2
50	81.1	150.3
Efficiency[%]	Produced heat [MWh/yr]	
	min	max
35	64.9	120.2
50	64.9	120.2
	Effective power [kW]	
	min	max
35	6.48	12.01
50	9.26	17.16

Table 6.4: Estimation of the produced electricity

The biogas installation is still consuming some of the electricity (see section 4.2). In most cases this is around 5% of the biogas total chemical energy.

As described in scenario N3 (see section 5.3), it is profitable to install PV panels on the installation and feed the digester with the produced electricity. The PV will be coupled with a battery to provide a constant electricity supply.
In Table 6.5 the PV and battery combination which was found to be the most profitable for each case is presented.

Efficiency[%]	Electricity less digester needs[MWh/yr]	
	min	max
35	49.5	91.7
50	73.8	136.8
Efficiency[%]	Heat less digester needs[MWh/yr]	
	min	max
35	38.8	94.1
50	38.8	94.1
Efficiency[%]	Electricity less digester needs (with PV) [MWh/yr]	
	min	max
35	55.1	102.1
50	79.4	147.1
Efficiency[%]	PV [kW] (roof area [m^2]) and battery size [kWh]	
	min	max
35	7.2 (50)/ 15.6	13.4 (93)/ 29.0
50	7.2 (50)/ 15.6	13.4 (93)/ 29.0
Efficiency[%]	PV electricity grid injection [kWh]	
	min	max
35	9.2	17
50	9.2	17

Table 6.5: Estimation of the grid-injected electricity

An estimation on the net present value of each case is presented in Table 6.6. All the projects will not yield any returns, as shown by the positive value of the NPV. Furthermore, as the cost of the biogas facility is proportional to the chemical power, the two estimations (min and max) differ.

Efficiency[%]	NPV [CHF]	
	min	max
35	294,800	388,274
50	253,676	312,095

Table 6.6: Estimation of the net present value

Location:
The biogas installation has to be installed on campus where unfortunately there is not a lot of empty space available. Furthermore, for reasons of hygiene, comfort and security, the digester should be placed at a reasonable distance of the classrooms and offices.

During a meeting with the managers for sustainable development of the EPFL [153], one place was mentioned which could satisfy all the above cited criteria: the empty lot next to the heating station. It is used as a depository for various materials (mostly earth and construction materials) with sometimes even compost.

Figure 6.5 is a satellite picture of the campus. The participating cafeterias are represented with a red point and the potential installation site with a green one.

Figure 6.5: Satellite picture of the EPFL campus - the red points are pick-up places, the green one is the location of the potential biogas facility

If the contract with the city of Lausanne were to be resigned, the EPFL would have to hire a company or let an EPFL employee take care of the pick-up, emptying and cleaning of the containers. The proximity of the installation is an advantage for the collection of the FW. An employee could attach the containers behind each other (as with shopping trolleys) and transport them easily to the facility with a small vehicle. The frequency of collection could also be increased if necessary.

What is more, three collection points (UNIL Banane (1.2 km), FMEL (3.6 km) and Geopolis (1.4 km)) are far away from the potential site (see Figure 6.6). The idea mentioned above wouldn't necessarily work, as the distances are greater (3.6 km maximum) and main streets have to be crossed. However 3.6 km is only 7 minutes of driving (according to Google Maps) and this could be done if the containers are properly sealed.

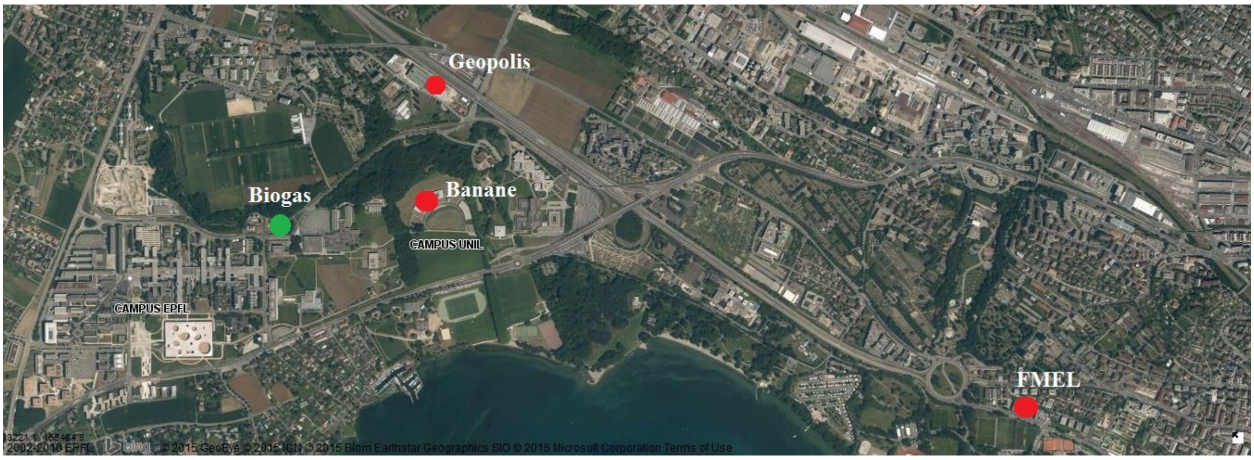


Figure 6.6: Satellite picture of the EPFL-UNIL campus, the red points are the more distanced pick-up places, the green one is the location of the potential biogas facility

The CHP installation (Centrale de chauffe) (on Figure 6.7) consists of 2 gas turbines running on natural gas and heat pumps using the lake as a heat sink and as a heat source. On the east side, there is a pile of compost, which occasionally will emit a strong smell. Since the Metro M1 passes a few meters south of it the biogas facility might be installed here.

Figure 6.7: Satellite picture of the EPFL CHP installation - potential biogas site on the east side

As the digester and the digestate pit sizes are known, a first plan of the installation could be drawn to scale. This will help to estimate if there is enough place for the chosen site, or if another one needs to be searched for, keeping in mind that the highest estimations should be an indicator for the volume of such a facility.

The pit and the storage should be built underground, as the sizes are objectively small and it should not pollute the view of the campus. On the other hand, most small-scale biogas digesters are built overground with pre-built systems, as the costs of digging and of the concrete makes the whole facility too costly. But in this case, the long-term aspect is more important: the campus will grow in size and will become better known, and with the pits being underground, it will appear more professional and in fact more pleasant.

The biggest pit will be for the digestate (129 m^3) and it will be taken to determine the depth of the installation. A single depth will be chosen, in order to facilitate the construction. The pit will be designed as a cube with sides of 5.05 m. The cubical form allows for an efficient use of agitators. The digester in turn will have an adapted depth and the two sides will be 2.68 m long.
At this point a feature may be added, which is never present at biogas stations: a heat exchanger between the cold incoming substrate (from outside into the digester)and the hot outgoing digestate. It is described in section 4.2 that around 30% of the biogas energy needs to be injected in the digester in form of heat. This value is extremely high and can be optimised. The most obvious solution is to have a kind of pre-heater, a heat exchanger could cool down the liquid digestate, which will be at 55 °C if at thermophilic level and heat up the substrate, which will be at ambient temperature. If this is done, a great amount of heat can be used in a different way. For example, the digestate

could be dried in an evaporator (see section 1.1.8), reducing the necessary storage volume.
The HEX's size is dependent on the desired temperatures, on the heat transfer coefficients, on the mass flows and on the HEX's design. As this is not the goal of this project a simple approximation is applied here.
The collected quantity of FW and the outgoing digestate over a 3 days period will be used in the pre-heater, the size of which is the sum of both. The masses are 633 kg of FW per day and 494 kg of DFW per day. For 3 days and by dividing by their specific density, the total volume is estimated to be 5 m^3. For a conservative estimation, the double has been taken. Furthermore, this will account for the HEX's tubes, the auxiliary equipment and maybe a small pre-storage for the substrate. Using the chosen depth of 5.05 m, the two sides will be 1.41 m long. Finally the digester will have the dimensions of 5.05 m x 2.68 m x 2.68 m (36.3 m^3).
Before reaching the balloon, the biogas should be dried, which is usually done with a condensate trap.
The gas-cleaning, the control station and the SOFC will be placed in a standard container (6 m x 2.6 m x 2.44 m =38 m^3). Finally, a gas-balloon should be included as a biogas storage, in case of higher or lower production or maintenance of the equipment. The balloon does not need to be very big and it would be sufficient to install it in a similar container.
The FW will have to undergo a hygienisation before entering the digester. This process is regulated by the law and is obligatory when handling processed animal by-products. It consists of a fine chopping of the FW, followed by a one-hour cooking at 70°C. This process will be performed at each collection (as the FW cannot be stored for a long time). A good estimation of the size of the hygienisator is the total volume of the food waste per collection, which was estimated above to be around 5 m^3 (1.9 t) if the pick-up is performed every 3 days. The unit could be installed in the same container as the SOFC which will provide it with heat.
In Figure 6.8 and Figure 6.9 a plan to scale and a flowsheet of the installation are presented.

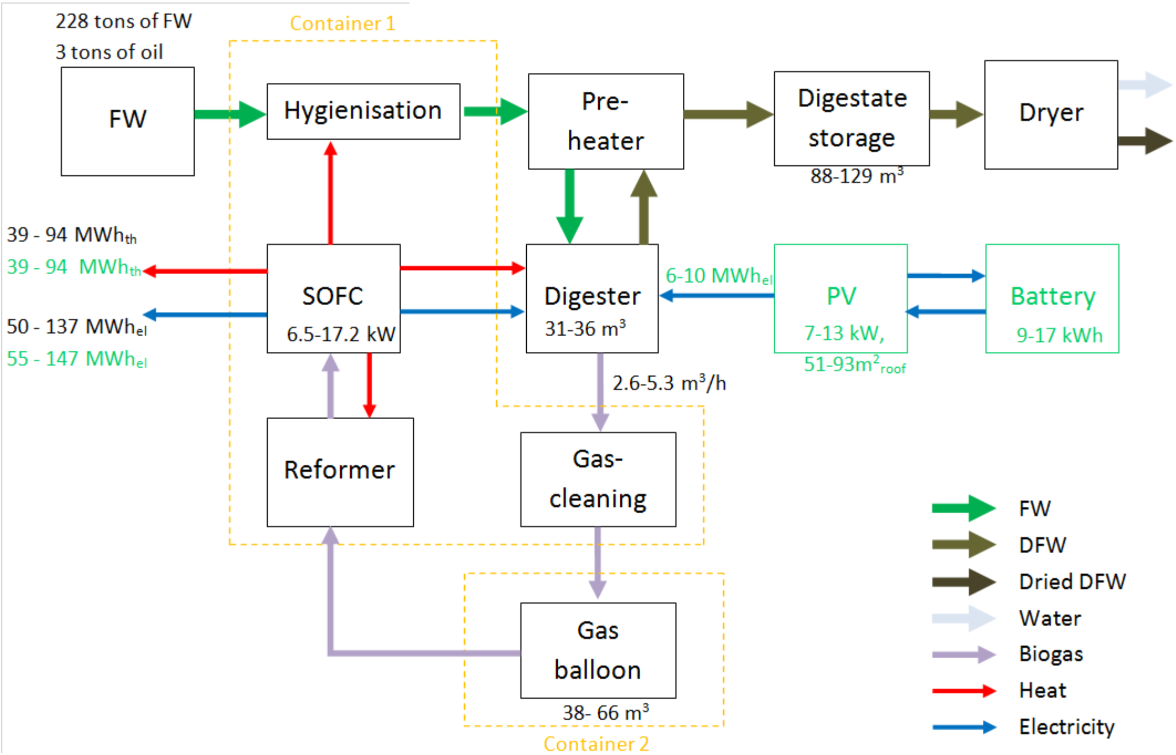


Figure 6.9: Flow scheme of the biogas SOFC installation

Figure 6.8: Plan to scale of the potential biogas installation [64]

Concerns:
There are some factors that have to be taken into account, to ensure the legality and the conformity of the installation:

- Protection of the environment: the facility will have to respect the same legal dispositions as an agricultural installation in terms of the protection of the environment. (impermeable floor, anticipation of leakages and toxic gas emissions, a security pipe from the digester to an empty (or big-enough) pit).
- Odour control: the scent is probably the greatest concern. All of the approached Swiss farmers say they had received numerous complaints from the neighbouring residents and shops before the project was approved [5]. It takes a few years to resolve the conflicts and satisfy all parties. This is why a solution has to be proposed before any dispute arises. As the gases resulting from FW are mainly composed of aromatic gases [73], the odour can be dealt with by using biotrickling filters and other gas filters (see section 1.1.4). It can also be reduced through proper management of the biogas installation: e.g. a sealed digester, pits and containers, very short openings of the previous and only when necessary, the waste should be unloaded in a closed room preferably with partial vacuum possibilities, etc. The biogas will have to be extensively cleaned, because of the fuel cell's requirements, thus no particular attention will have to be spent on the exhaust gas.

Moreover, a report of the Danish Environmental Protection Agency [74] estimated the cost of preventing odour nuisances, which amounts to a maximum 2 % of the construction costs, and 0.5 % of the total operating costs. The report continued arguing that the odour is mainly caused by unintended gas leakages and emission of of air which has not been cleaned properly. Furthermore, the Danish EPA has imposed a 5 odour unit per cubic meter standard in residential areas.
The preferred distance to residential areas is 500 meters, nonetheless 100 metres are also acceptable if the plant is well-managed [74] .

Building permits and legal requirements:
A first contact with the Federal Department of the Environment, Transport, Energy and Communications (DETEC) [123] was made in order to inquire which legal dispositions need to be met, and who they need to be discussed with. The answer to this question is discussed below. Furthermore, the previously mentioned concerns are also addressed.
First of all, if the biogas installation wants to benefit from the RPC, then a series of legal requirements need to be fulfilled. These laws are on a federal level and are enumerated in the "Manuel Qualité Biogaz" [122] in the Energy Regulation (fr: *Ordonnance sur l'énergie (OEne)*) [124].
The main laws to follow are on the subject of the protection of the environment, the territory planning, the waste treatment, the movement of wastes, the elimination of animal by-products, the noise protection, the circulation of fertiliser, the use of vegetable oil,and the gas odorisation.
They are all listed in Annex A.

Secondly, licensing issues for the construction of biogas facilities are to be checked with the cantonal authorities.
Consequently, the general administration of the environment of the canton the Vaud have been consulted in order to clarify which authorisations need to be fulfilled [125].
The installation of biogas would process more than 100 tons of waste per year, thus will be submitted to a cantonal authorisation. Furthermore, the described biogas installation is similar to an agricultural biogas facility [125], hence a check-list on this behalf can be consulted.
The check-list is presented in Annex A.

[5]Most of them were odour-related concerns, with some fearing it would reduce the value of the nearby land and some concerns about visual pollution

The conclusion, after consulting these two documents, can be summarised in seven points:

1. More than 100 tons of waste are processed each year, making the biogas installation fall under cantonal authorisation. The facility will legally be a waste treatment plant.
2. Being a waste treatment plant, the installation will need special authorisation (from the Department of Security and Environment), it cannot be built in or around areas of protection of groundwater, the plant has to be enclosed and under surveillance, finally all the inputs have to be verified, classified and the results need to be shared yearly with the cantonal authorities.
3. Kitchen FW (fr: *lavures*) are considered as animal by-products, which asks for certain requirements. The number of legal bases and the points to respect are relatively numerous: the plant will need an authorisation from the service of consumption and of veterinary affairs (SCAV, Service de la consommation et des affaires vétérinaires), and various technical rules (as described in the annex of the OESPA (Ordonnance fédérale sur l'élimination des sous-produits animaux)) have to be respected. These many rules touch on almost all the parts of the installation (e.g. they concern the conception of the site, the necessary equipment, the cleaning and the disinfecting, the exploitation of the plant and the methods of transformation of the animal by-products).
4. The food oils and fats (fr: *huiles et matières grasses alimentaires*) are wastes " subject to control " under federal law. Their treatment will require another cantonal authorisation (SESA: Service des eaux, sols et assainissement).
5. According to the principles of the OPair (Ordonnance fédérale sur la protection de l'air), the neighbourhood must be preserved from excessive odour emissions. All the necessary preventive measures need to be taken in order to limit their emissions. In case of substantiated complaints, additional measures may be prescribed. The laws do not include a limit odour quantity, thus each case highly depends on the received complaints.
6. The digestate is considered as a fertiliser of recycling products (fr: *engrais de recyclage*) under law, so several laws and controls need to be applied in that case. The digestate's pollutants, nutritive elements and heavy metals need to be analysed at least once a year (depending on the processed quantity). The values cannot exceed certain limits and they need to be communicated to the OFAG (Office fédérale de l'agriculture).
7. Furthermore, the amount of organic micro-pollutants and foreign objects (rocks, glass, metals, plastics) of the digestate also has to be measured and it cannot exceed a certain limit

Finally, the Confederation is writing a report [127] aiming at aiding the development, the implementation and the execution of a biogas installation [129]. The report is not finished yet, but will contain the main laws to obey. A provisional document was given to the author [127] and a copy may be asked from the OFEV, OFAG or from the author.

General			
Total FW collected 2014	m_{FW}	$t \cdot yr^{-1}$	228
FW collected - EPFL 2014	$m_{FW\ EPFL}$	$t \cdot yr^{-1}$	119.4
FW collected - UNIL 2014	$m_{FW\ UNIL}$	$t \cdot yr^{-1}$	108.6
Total FW collected 2013	m_{FW}	$t \cdot yr^{-1}$	181.2
FW collected - EPFL 2013	$m_{FW\ EPFL}$	$t \cdot yr^{-1}$	79.6
FW collected - UNIL 2013	$m_{FW\ UNIL}$	$t \cdot yr^{-1}$	101.6
Total vegetable oil collected 2014	m_{oil}	$t \cdot yr^{-1}$	3
for 2014 only - EPFL & UNIL			
Average pick-up period	$T_{pick-up}$	days	3.368
Average FW collected per pick-up	$m_{pick-up}$	t	2.38
Daily FW production	$m_{daily\ FW\ tot}$	$kg \cdot day^{-1}$	633
Yearly FW production - EPFL member (staff & student)	$m_{yearly\ FW\ EPFL\ member}$	$kg \cdot yr^{-1} \cdot head^{-1}$	8.73
Yearly FW production - UNIL member (staff & student)	$m_{yearly\ FW\ UNIL\ member}$	$kg \cdot yr^{-1} \cdot head^{-1}$	6.57
Working day (261 d/y) FW production - EPFL member	$m_{work\ day\ FW\ EPFL\ member}$	$g \cdot day^{-1} \cdot head^{-1}$	33.4
Working day (261 d/y) FW production - UNIL member	$m_{work\ day\ FW\ UNIL\ member}$	$g \cdot day^{-1} \cdot head^{-1}$	25.2
Working day (261 d/y) FW production - total	$m_{work\ day\ FW\ total}$	$kg \cdot day^{-1}$	873.6
Digester and storage			
Over-dimensioned for an increase in FW production	α_{FW}	%	130
Over-dimensioned for a maximum fill-up	$\alpha_{fill-up}$	%	120
Total over-dimensioning of the digester	α_{total}	%	156
Considered retention time for FW	$\tau_{retention}$	days	30
Mass of FW in the digester after $\tau_{retention}$=30 days	$m_{FW\ digester}$	$t \cdot \tau_{retention}^{-1}$	25
Mass of digestate leaving the digester after $\tau_{retention}$=30 days	$m_{digestate}$	$t \cdot \tau_{retention}^{-1}$	19.3
Mass of biogas leaving the digester after $\tau_{retention}$=30 days	m_{biogas}	$t \cdot \tau_{retention}^{-1}$	5.4
Volume digester - smallest estimation	$V_{digester\ min}$	m^3	30.8
Volume digester - highest estimation	$V_{digester\ max}$	m^3	36.3
Volume DFW pit - 5 month storage - smallest estimation	$V_{DFW\ pit\ min}$	m^3	88
Volume DFW pit - 5 month storage- highest estimation	$V_{DFW\ pit\ max}$	m^3	129
Substrate properties			
VS in proportion of wet FW mass - smallest estimation	$VS_{FW\ min}$	%ofwetmassFW	8
VS in proportion of wet FW mass - highest estimation	$VS_{FW\ max}$	%ofwetmassFW	27
VS in proportion of wet FW mass - most common	$VS_{FW\ common}$	%ofwetmassFW	20
VS in proportion of vegetable oil mass	VS_{oil}	%ofoilmass	84
Methane yield of FW per VS - smallest estimation	$Y_{FW\ VS\ CH4\ min}$	$m^3_{CH_4} \cdot kg^{-1}_{VS}$	0.3
Methane yield of FW per VS - highest estimation	$Y_{FW\ VS\ CH4\ max}$	$m^3_{CH_4} \cdot kg^{-1}_{VS}$	0.6
Methane yield of vegetable oil per VS	$Y_{oil\ VS\ CH4}$	$m^3_{CH_4} \cdot kg^{-1}_{VS}$	0.94
Methane yield of FW - smallest estimation	$Y_{FW\ CH4\ min}$	$m^3_{CH_4} \cdot kg^{-1}_{wet\ mass}$	0.06
Methane yield of FW - highest estimation	$Y_{FW\ CH4\ max}$	$m^3_{CH_4} \cdot kg^{-1}_{wet\ mass}$	0.12
Methane yield of vegetable oil	$Y_{oil\ CH4}$	$m^3_{CH_4} \cdot kg^{-1}_{wet\ mass}$	0.79
Methane energy density	Y_{CH4}	$kWh \cdot m^{-3}_{CH_4}$	10.11
Chemical energy of the FW's biogas - smallest estimation	$E_{ch\ FW\ biogas\ min}$	$MWh \cdot yr^{-1}$	133
Chemical energy of the FW's biogas - highest estimation	$E_{ch\ FW\ biogas\ max}$	$MWh \cdot yr^{-1}$	267
Chemical energy of the vegetable oil's biogas	$E_{ch\ oil\ biogas}$	$MWh \cdot yr^{-1}$	32
Biogas flowrate - smallest estimation (without over-dim.)	$V_{biogas\ min}$	$m^3 \cdot h^{-1}$	2.64
Biogas flowrate - highest estimation (without over-dim.)	$V_{biogas\ max}$	$m^3 \cdot h^{-1}$	5.28
Fuel Cell - SOFC			
Electrical efficiency SOFC	$\varepsilon_{SOFC\ elec}$	%	50
Installed power - smallest estimation	$P_{SOFC\ min}$	kW	9.26
Installed power - highest estimation	$P_{SOFC\ max}$	kW	17.16
Electrical efficiency SOFC	$\varepsilon_{SOFC\ elec}$	%	35
Installed power - smallest estimation	$P_{SOFC\ min}$	kW	6.48
Installed power - highest estimation	$P_{SOFC\ max}$	kW	12.01

Table 6.7: Summary of the results

Conclusion

The use of fuel cells for valorising agricultural and food-waste-derived biogas in Switzerland has been studied. It appears that the Swiss agricultural case is characterised by farms with small numbers of animals (20 cows) and high feed-in tariffs for biogas derived electricity.
It has been shown that solid oxide fuel cells become competitive over combustion engines if the investment cost of the first decreases to 13,000 CHF/kW$_{el}$ with a lifetime of 10 years.
However, a small-scale biogas installation becomes only profitable if the farm size is doubled, the electrical efficiency of the SOFC increased to 50% and the investment cost reduced to 8,000 CHF/kW$_{el}$ for a lifetime of 12 years. Besides, the biogas facility needs to see a 40% drop in the investment cost. Choosing a fuel cell over an ICE allows to increase the electrical production by 130%. If combined with PV, the figures rises to 151%. Scaling up the use of fuel cells to small-scale agricultural sites in Switzerland allows to produce 1,700 GWh of electricity, more than double if equipped with ICE. The main challenge is to bring down the lifetime cost of the fuel cells and to reduce the investment cost of small-scale biogas facilities to around 6,000 CHF/kW$_{ch}$.

The case of equipping the EPFL and UNIL campuses with a digester and a SOFC is considered feasible from a technical and legal point. Each year 228 tons of food waste are collected and 3 tons of vegetable oil, which amounts to fuel a SOFC in the range of 6.5 - 17.2 kW continuously on biogas, producing 50 - 150 MWh of electricity. The main challenge is not the conception of the plant, but the legal aspect around it. It may take several years to get all the necessary permits and authorisations from the different federal and cantonal administrations.

Based on the present study, fuel cells seem to be a promising technology to tap the Swiss biogas potential.
The project might contribute to a solution in the domain of reducing GHG emissions, as unmanaged manure and organic wastes play an important role in global warming. By valorising them, emissions are avoided and new energy sources are created.
Building experimental prototypes allows to promote their case and create local know-how, which may lower their lifetime cost.
The EPFL and UNIL campus has been shown to offer the technical potential for the implementation of a biogas powered fuel cell installation. This first-of-its-kind Swiss installation might revive the interest in both biogas and solid oxide fuel cells, and could lead the way for future similar projects.

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A. Annex A

Choi and Okos established a correlation to calculate various proprieties of food products depending on the composition and the temperature (specific heat, thermal diffusivity and conductivity, and density). The density of a sample $\rho(T, x)$ can be described by a function of the densities $\rho_i(T)$ and weight fraction x_i of the main components i (for example: Water, crude fat, crude protein, crude fibre, crude ash and Nfe):

$$\begin{aligned} &\rho(\mathrm{T}, \mathrm{x}) = [\Sigma(\mathrm{x_i}/\rho_\mathrm{i}(\mathrm{T}))]^{-1} \\ &\quad with \\ &\rho_\mathrm{i}(\mathrm{T}) = C_1 + C_2 \cdot (T/K - 273.15) \end{aligned} \tag{A.1}$$

This equation has been improved by Gerber and Schneider, who calculated more accurate coefficients. They did not calculate the density of water using the polynomial equation, but used the preciser IAPW-95 formulation.

The coefficients are the following:

Component	Coefficient	
	$C_1(kg/m^3)$	$C_2(kg/m^3)$
Crude protein	861.06	5.2834
Crude fat	3111.0	-8.3323
Crude fibre	2434.3	-6.3984
Crude ash	691.80	2.9096
Nfe	478.76	24.319

Table A.1: The coefficient for the digestate's density

On-line measurements :
On-line measurements are vital for preserving the equipments and predicting the power production. The best installations have on-line measurements which can be checked instantaneously on an app and the plant manager (as well as the company) will receive an alert if a parameter is not at its optimal value. More robust ones take only the elemental on-line measurements (temperature, electricity,...) and a gas-probe is manually extracted (into a TECOBAG (PETP/AL/PE 12/17/75) or in a Nalophan NA bag [50]) to perform the necessary tests.
The most important measure is the amount of electricity produced by the CHP unit. It can be directly read from an electric meter. This is also the most common measurement device present in German installations (figure A.1). An optimised installation will have a power quality analyser which is connected to all the auxiliary units in order to know the own-consumption's distribution [47].

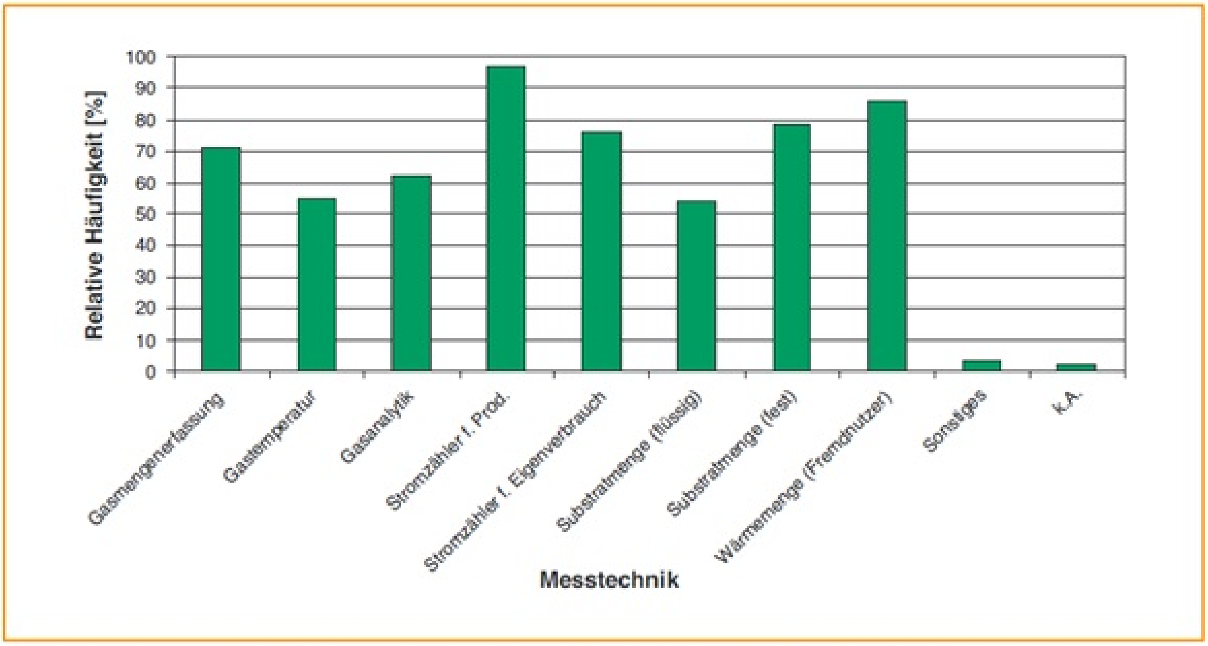


Abb. 3-15: Relative Häufigkeitsverteilung der an den Biogasanlagen installierten Messtechnik

Figure A.1: Relative frequency of different measurement techniques [43]

The second output of the biogas plant is heat and will also be accounted for, as it is a requirement in various countries to use a certain amount. On the other hand, installations having a conventional engine for CHP have a major problem: the engine shuts down if the methane percentage is less than 45-50%, as combustion will not be take place. Methane or CO_2 have to be measured. Luckily for the German plants, maize decomposes into a highly methan-rich biogas, thus this problem does not occur very often. CH_4, O_2 and CO_2 can be measured with an infra-red gas analyser [50].

Gas measurement systems (GMS) are the most frequently used for establishing anaerobic biodegradability. The methods are either manometrically, meaning keeping the volume constant and measuring the pressure increase, or volumetrically, keeping the pressure constant and measuring the volume change. The rate and volume of gas can be measured using different techniques; volume displacement devices, lubricated syringes, manometers or pressure transducers, low pressure flow meters, manometer assisted syringes, automatic gas flow meters (mixed volumetric/manometric systems) or a digital pressure transducer (OxiTop®(WTW, Germany)) [51].

There are several methods and standards for determining crucial digestion parameters, they are listed below: For the estimation of dry residue and water content (TS/DM), the standards EN 12880 and APHA 2540 B are used, which involves drying the sample in a drying chamber at 103-105°C to constant weight. The estimation of the Volatile Solids (VS) and organic dry matter (ODM) is done with the standards EN 12879 and APHA 2540 E. It involves the previous process; the samples, after dried, are ignited to constant weight in a muffle furnace at 550°C. However, the last parameters cannot be determined with accuracy, as part of the volatile solids will leave the sample during the drying step. Finally Biochemical Methane Potential (BMP, total possible methane yield of a feedstock) and Chemical Oxygen Demand (COD, total possible energy content of a feedstock) can be determined using different standards (EN 11734, DIN 38 414 (S8) and VDI 4630 for BMP and DIN 38 414 (S9) and APHA 5220 B for COD. [98]

A short list of companies, offering on-line measurement equipment for biogas or other gases, is listed below:

- Awite Bioenergy GmbH
- Sensortran
- Izasa
- Matelco

High efficiency at partial load for the FC :
The current-voltage profile can be divided into two parts; a first linear part due to voltage losses (caused by the internal cell resistance) and a second non-linear part due to the current loss. At partial load, the current is reduced due to the diminished fuel flow. Hence the operating current is shortened to the left (see figure on the right) and the operating voltage is actually increased, thus the total efficiency is increased.

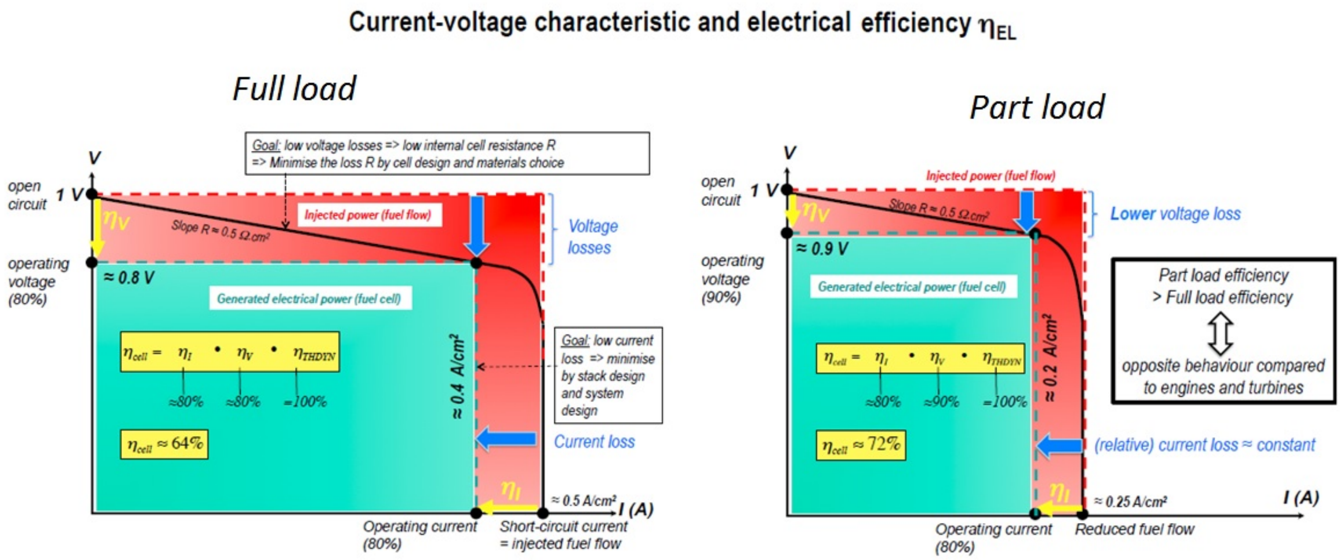


Figure A.2: Difference between the efficiency at full and partial load for a FC, [76]

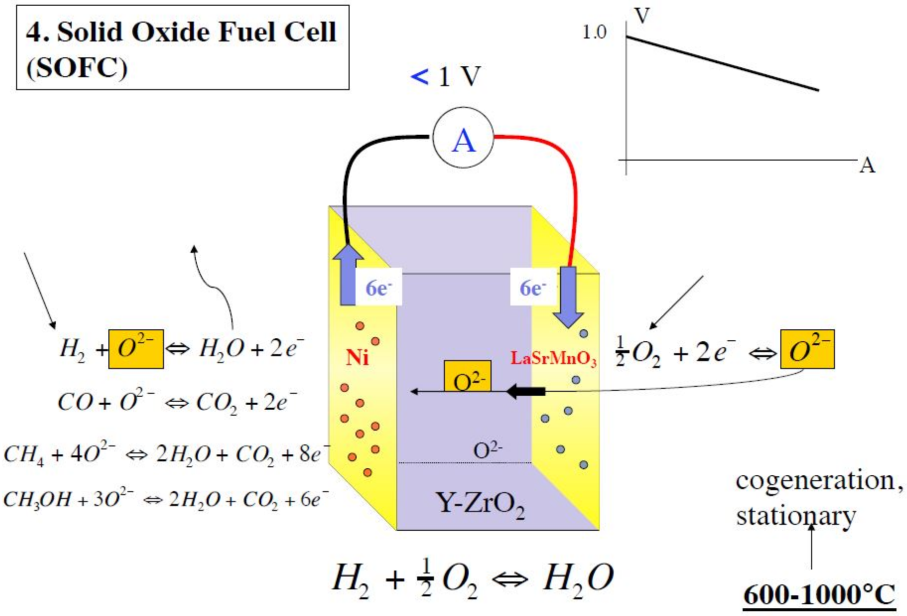


Figure A.3: Schema of the operation of a SOFC, figure from [76]

Anlage_Projekt-Bezeichnung	Anlage_Energieträger	Anlagentyp	Leistung [kW]	Produktion [kWh]**	Vergütung 2014 [CHF]	Anmeldedatum	Anlage_Inbetriebnahme-Datum	Anlage_Vertragsend
natürliche Person	Biomasse	übrige Biomasseanlage	5,1	14 640	4 465	23.04.09	28.06.10	31.12.30
natürliche Person	Biomasse	übrige Biomasseanlage	5,5	8 748	2 668	02.12.08	27.10.06	31.12.14
natürliche Person	Biomasse	übrige Biomasseanlage	11,0	1 243	479	27.12.10	15.10.13	31.12.33
natürliche Person	Biomasse	übrige Biomasseanlage	16,0	46 052	22 335	02.05.08	01.03.06	31.12.26
juristische Person	Biomasse	übrige Biomasseanlage	25,0	69 737	32 079	23.03.09	01.10.09	31.12.29
natürliche Person	Biomasse	übrige Biomasseanlage	26,0	177 909	86 286	06.11.08	20.03.10	31.12.30
natürliche Person	Biomasse	übrige Biomasseanlage	29,9	226 011	109 615	26.08.08	29.08.12	31.12.32
BHKW Ökostrom Scherer A	Biomasse	übrige Biomasseanlage	30,0	33 083	9 263	16.06.09	03.01.07	31.12.27
B Biogasanlage Mooshof R	Biomasse	übrige Biomasseanlage	37,0	173 916	78 101	02.05.08	01.09.09	31.12.29
Agrogas Furttal	Biomasse	übrige Biomasseanlage	40,0	268 449	146 130	02.05.08	06.11.08	31.12.28
B Steiner A. + Cie AG - Blo	Biomasse	übrige Biomasseanlage	45,0	54 221	19 329	16.09.10	16.11.12	31.12.32
BHKW Kilian Aebischer Hei	Biomasse	übrige Biomasseanlage	60,0	391 779	175 938	02.05.08	22.08.11	31.12.31
Biogasanlage Götschi Trub	Biomasse	übrige Biomasseanlage	60,0	443 933	200 195	02.05.08	30.11.08	31.12.28
Biomasse Christian Flach -	Biomasse	übrige Biomasseanlage	60,0	238 426	109 676	18.06.08	01.03.07	31.12.27
BHKW Sunnmatt Studer Zv	Biomasse	übrige Biomasseanlage	64,0	402 906	171 608	02.05.08	14.12.11	31.12.31
B Grass-Biogas und Servic	Biomasse	übrige Biomasseanlage	70,0	81 478	34 703	21.01.11	06.10.11	31.12.31
BHKW Reto Grossenbache	Biomasse	übrige Biomasseanlage	75,0	264 105	118 603	19.02.09	01.02.10	31.12.30
Biogasanlage Gutenswil	Biomasse	übrige Biomasseanlage	75,0	508 381	234 935	02.05.08	22.04.13	31.12.33
Biogasanlage Zuoz	Biomasse	übrige Biomasseanlage	75,0	229 615	97 799	02.05.08	23.12.07	31.12.27
*Biogas ESR AG Hildisriede	Biomasse	übrige Biomasseanlage	90,0	356 115	145 414	25.09.08	17.09.13	31.12.33
*Biogas Jakob Estermann H	Biomasse	übrige Biomasseanlage	90,0	98 210	40 102	25.09.08	17.09.13	31.12.33
Bestehende Biogasanlage	Biomasse	übrige Biomasseanlage	90,0	688 711	293 918	02.05.08	01.06.08	31.12.28
Kompogas-Anlage Langent	Biomasse	übrige Biomasseanlage	90,0	529 713	130 090	02.05.08	01.04.07	31.12.27
Biogaz Karlen Frères Vuite	Biomasse	übrige Biomasseanlage	95,0	691 190	320 665	02.05.08	01.08.08	31.12.28
B Biogas Kaltbrunn GmbH -	Biomasse	übrige Biomasseanlage	100,0	19 612	8 571	18.11.10	13.12.04	31.12.24
BHKW Naef Biogas AG Fric	Biomasse	übrige Biomasseanlage	100,0	765 274	347 084	02.05.08	09.03.10	31.12.30
BHKW Winzeler Thayngen	Biomasse	übrige Biomasseanlage	100,0	580 268	250 912	02.05.08	15.11.04	31.12.24
Biogasanlage Davos	Biomasse	übrige Biomasseanlage	100,0	474 137	201 947	05.05.08	24.11.04	31.12.24
Biogasanlage Hawisa Gmb	Biomasse	übrige Biomasseanlage	100,0	508 312	228 270	02.05.08	25.08.06	31.12.26
Biogasanlage Jordi	Biomasse	übrige Biomasseanlage	100,0	307 858	87 292	02.05.08	22.11.06	31.12.26
Biogaz Agricole Saugealles	Biomasse	übrige Biomasseanlage	100,0	461 750	196 671	19.05.08	01.04.07	31.12.27
Wärme-Kraftkoppelungsan	Biomasse	übrige Biomasseanlage	100,0	479 845	217 717	02.05.08	18.12.06	31.12.26

Figure A.4: List of the Swiss biogas installations (< 101 kW_{el}) receiving a feed-in tariff, [159]

Micro-turbines :
Another possibility to convert biogas is using a micro-turbine. Even though it is an established technology for higher capacities, small turbines (micro-turbines) start to get market ready at powers around 30-120 kW_{el}. Their electrical efficiency is in the order of 25 - 30 %, with a total efficiency of 75 - 91%. Furthermore, their investment cost is way higher than that of ICEs, but micro-turbines are profitable in the long run (thanks to higher efficiencies, lower maintenance cost and longer lifetimes) [32].
The available products are the following:

Manufacturer / Model	Electrical Power kW_{el}	Electrical Efficiency [%]	Thermal efficiency [%]	Total efficiency [%]	Reference
Captsone C30	30	26	64	90	[148]
Elliott Turbo SVSS	50	28	-	-	[150]
Turbec T100 Microturbine	100	30	47	77	[151]

Table A.2: Characteristics of different MT (for NG)

Summery of the report commission by the Swiss Federal Office of Energy on the agricultural biogas potential [17] :

Location:
44% of the Swiss farmers are situated in plain areas
41% are situated in mountainous areas (I to IV)
Area:
10% have a surface between 5 and 10 ha
36% between 10 and 20 ha
25% between 20 and 30 ha
12% between 30 and 40 ha
10% have a surface higher than 40 ha
Animals:
70% of the farmers have cattle
55% have dairy cows
20% have suckling cows
12% have porks
Manure:
53% of the dairy farms produce only liquid manure (FR: *lisier*)
46% of the dairy farms produce solid manure and slurry (FR: *fumier et purin*)
Biogas potential:
total potential lies at 4'409 GWh per year
divided into
64.2% from cattle manure
12.7% from pork manure
23.1% from intermediate cultures and chuff

Table A.3: Average Swiss farmer according to the OFEN Mini-biogas study [17]

It is possible to determine the biogas energy yield in function of the number of cattle for different production zones. In the report commissioned by the Swiss Federal Office of Energy (SFOE) [17], six zones have been identified: plain area, hilly area, and mountain area I-IV. This distinction is important as the manure production is dependent of the time the cattle spends in the barn - the only time it can be collected. For this reason, the pasture and summering have to be deduced in the calculations. Finally the type of stables has to be accounted for as each one produces a different kind of manure:

Type of stalls	Stanchion barn		Free stalls barns		Deep litter-loose housing
Type of the manure	Liquid manure only	Manure and purin	Liquid manure only	Purin et fumier	Purin et fumier

Table A.4: Types of stables and resulting type of manure [17]

The last category is the type of cow: dairy cow, suckler cows, beef cattle <1year, beef cattle 1-2 years, beef cattle >2 years and suckling calf.

A detailed analysis of the 57,617 Swiss farms revealed that 44% of them are situated in plain territory and 41% in mountainous zones (I-IV). Furthermore, of the total mass of produced manure in Switzerland, 87% comes from cattle (representing 80% of the biogas potential). Only cattle in plain territory are considered in this study, as they represent 49.7% of the Swiss biogas potential.

In the following table, the quality and quantities of manure for different cattle are presented.

Multiplying a substrate's methane potential [kWh/t MB] with its annual quantity [t/year] gives the total biogas potential. The mass is deduced from the volume with the density of liquid manure and slurry which is estimated to be 1 (t/m^3) [32].

Categories	Annual production				
	Liquid manure [m^3]	Slurry and manure		Deep layer	
		Slurry [m^3]	Manure [t]	Manure [t]	Slurry [m^3]
Dairy cow	17.3	8.6	6.7	11.7	5.0
Suckling cow	11.6	6.0	4.5	9.4	4.0
Beef cattle <1 yr	5.5	2.6	2.0	3.6	1.4
Beef cattle 1-2 yr	6.0	3.0	2.3	4.7	2.0
Beef cattle >2 yr	8.3	4.1	3.0	7.0	3.0
Calf suckling >2 yr	-	1.4	1.1	2.1	0.9

Table A.5: Types of stalls and resulting type of manure [17]

Substrate	Potential [kWh/$t_{wet\,mass}$]
Liquid manure dairy cow	153
Liquid manure suckling cow	153
Slurry	87
Manure stanchion- / free stalls barn	328
Manure deep litter-loose housing	364
Liquid manure - pork, fertiliser	90
Liquid manure - pork, livestock	83
Manure - pork	577
Intermediate crops	529
Chaff	1'961

Table A.6: Potential of each substrate [17]

Besides manure, farmers also have other potential substrates available on the agricultural site. Some are not economically beneficial to collect and to digest. The two main ones are listed below:

- intermediate crops (between two principal cultures the farmer is obliged to plant the fields with an intermediate crop). It is possible to estimate the average area of intermediate cultures in function of the total size of the agricultural site. Considering an average yield of 15 tons per ha with 20% MS, 3 tons of MS per ha of intermediate crops is the considered yield [17].

Size	Average intermediate culture area per zone and per exploitation category [ha]		
	Plain zone	Hill zone	mountainous zone1
<1ha	0.1	0.0	0.0
1ha - 3ha	0.3	0.1	0.0
3ha - 5ha	0.6	0.2	0.1
5ha - 10ha	1.2	0.3	0.2
10ha - 15ha	2.0	0.6	0.2
15ha - 20ha	2.8	0.8	0.3
20ha - 25ha	3.6	1.0	0.4
25ha - 30ha	4.4	1.3	0.5
30ha - 40ha	5.5	1.6	0.7
40ha - 50ha	7.2	2.0	0.9
50ha - 70ha	9.4	2.7	1.2
70ha - 100ha	13.1	3.6	1.6
>100ha	25.2	5.5	2.8

Table A.7: Average area for intermediate culture [17]

- chaff (During the harvest of cereals, and specifically seed harvest, the straw is collected, usually used for mulching stables. Tiny straw (twig straw, broken kernels, bard, etc.) called chaff, remains on the field. The recovery of the chaff presents agronomic advantages). The average size of the cereal fields in function of the total size of the farm is presented in Table A.8. The yield of chaff is 1 ton per ha [17].

Size	Average cereal field area per zone and per exploitation category [ha]					
	Plain zone	Hill zone	MZ 1	MZ 2	MZ 3	MZ 4
<1ha	0.0	0.0	0.0	0.0	0.0	0.0
1ha - 3ha	0.8	0.7	0.2	0.3	0.0	0.0
3ha - 5ha	1.0	0.8	0.4	0.3	0.1	0.0
5ha - 10ha	1.5	1.2	0.9	0.6	0.5	0.0
10ha - 15ha	2.1	1.7	1.2	0.9	0.7	0.2
15ha - 20ha	2.7	2.1	1.7	1.1	0.8	0.0
20ha - 25ha	3.3	2.7	2.1	1.4	0.6	0.3
25ha - 30ha	4.0	3.1	2.7	1.9	1.3	0.0
30ha - 40ha	5.1	3.9	3.8	2.1	0.9	0.0
40ha - 50ha	6.6	5.1	5.0	2.6	1.1	0.7
50ha - 70ha	8.6	7.3	5.3	3.3	1.4	0.4
70ha - 100ha	12.6	11.9	6.4	6.6	1.5	0.0
>100ha	22.2	18.0	14.4	6.7	0.0	1.5

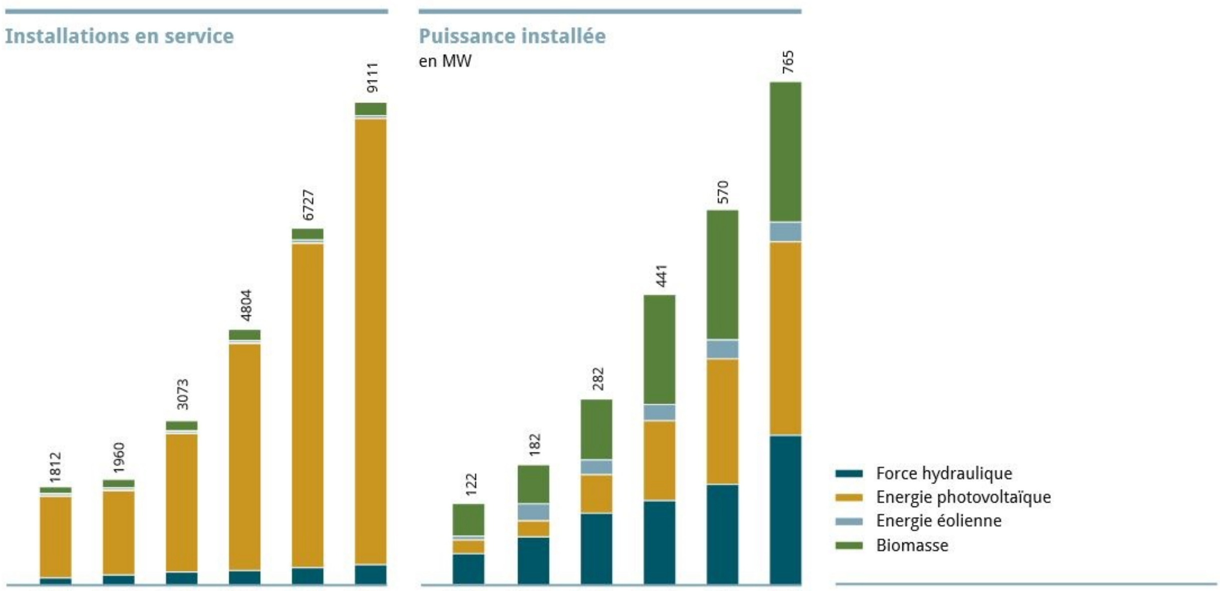
Table A.8: Average cereal field area per zone and per exploitation category [17]

Table 3 – Characteristic of the fuel cells [29–31].

Characteristic	Cells at low temperature			Cells at high temperature	
	AFC	PEFC	PAFC	MCFC	SOFC
Electrolyte	Potassium hydroxide	Polymer membrane	Phosphoric acid	Lithium potassium/sodium carbonate	Doped zirconia oxide
Ion that promotes the reaction	OH^-	H^+	H^+	$CO_3^{=}$	$O^{=}$
Temperature, °C	60–120	70–100	160–220	600–650	800–1000
Catalyst	Pt/Pd, Ni	Platinum	Platinum	Nickel	Nickel
Oxidant	O_2	O_2/Air	O_2/Air	O_2/Air	O_2/Air
Electric efficiency (LCV), %	45–55	40–55	40–50	45–50	50–60
Advantage	High power density	High power density, Minimum problems of materials and corrosion	High efficiency in cogenerative applications	Availability of high temperature heat, High efficiency, Possibility of internal reforming	Availability of high temperature heat, High efficiency, Possibility of internal reforming,
Disadvantage	High purity of fuel gas	Problem of water management	Liquid corrosive electrolyte	Problems of life and stability of the materials, Required recirculation of CO_2	Ceramic–metal combinations induce high thermal stresses in stack
Gas composition					
H_2	F (pure)	F	F	F	F
CH_4	Poison	IG	IG	IG/F	F
CO_2	Poison	IG	IG	React	IG
CO	Poison	<10 ppm	<500 ppm	F	F
NH_3	F	<1 ppm	Poison	~1–3% vol	F
Particulate	<100 ppm	<100 ppm	<100 ppm	10–100 ppm	10–100 ppm
TAR	Poison	Poison	Poison	<2000 ppm	<2000 ppm
H_2S, COS	Poison	Poison	<50 ppm	<0.5–1 ppm	<1 ppm
Halogens	Poison	<1 ppm	Poison	<1 ppm	<1 ppm
Alkali metals	Poison	Poison	Poison	<1 ppm	<1 ppm

F = fuel; IG = Inert Gas; React = takes part in electrode reaction.

Figure A.5: Characteristics of different fuel cells, [100]



2009	2010	2011	2012	2013	2014	2009	2010	2011	2012	2013	2014	
140	196	244	280	334	392	46.5	73.2	109.6	128.9	153.9	228.3	Force hydraulique
1558	1609	2639	4316	6164	8468	20.6	25.4	58.5	120.7	190.0	293.4	Énergie photovoltaïque
6	18	17	16	17	18	2.0	24.9	22.9	24.2	29.5	30.5	Energie éolienne
108	137	173	192	212	233	52.6	58.5	91.1	167.2	196.5	212.6	Biomasse
1812	**1960**	**3073**	**4804**	**6727**	**9111**	**122**	**182**	**282**	**441**	**570**	**765**	**Total**

Figure A.6: Number of installation and total power by renewable energies under the RPC [118]

Figure A.7: Outside of a digester with air injection - Installation of Ackermann (Jura)- Picture by Dirk Lauinger

Figure A.8: Inside of a digester with air injection and presence of precipitated sulphur (yellow) - Installation of Ackermann (Jura)- Picture by Dirk Lauinger

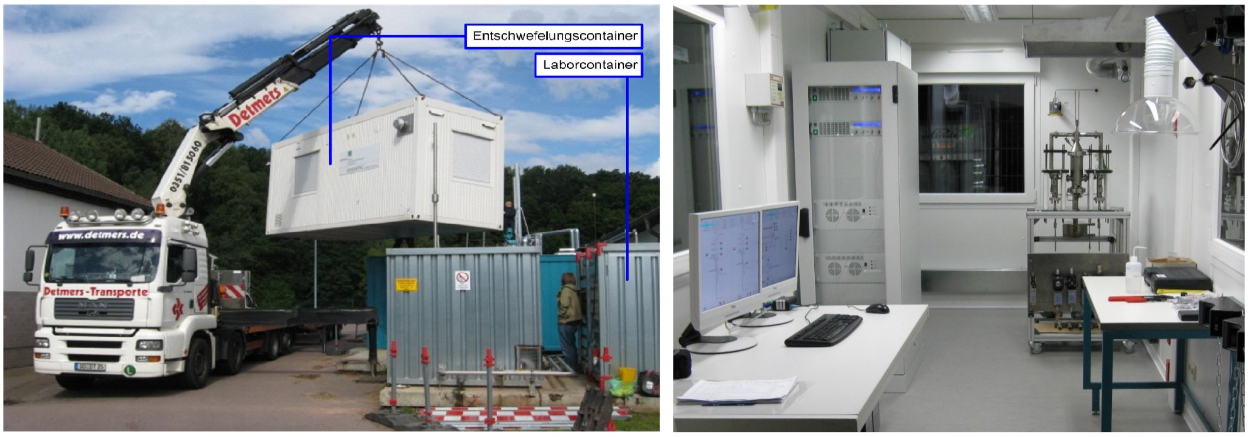


Figure A.9: Left: Lab-container during the installation in Roβwein, right: the inside of the container [97]

Component	DM [%]	VS of DM [%]	VS of wet mass [%]	CH_4 yield [m^3_{CH4}/kg_{VS}]	CH_4 yield [$m^3_{CH4}/kg_{wet\ mass}$]	Biogas [$m^3/kg_{w.m.}$]	Ref
Food remains	10	80	8	0.5	0.04		[52]
Food remains	10	80	8	0.6	0.048		[52]
Food remains				0.478			[54]
Food remains				0.472			[54]
Food remains				0.245-0.510			[54]
Food remains				0.425-0.4456			[54]
Food waste			24.1 (1.1)	0.353	0.085		[55]
Food waste	30.9		26.35	0.435	0.1146		[56]
Food waste	18.1 (0.6)		17.1 (0.6)				[57]
Food waste	23.1 (0.1)		21.0 (0.3)				[58]
Food waste	30.9 (0.07)		26.35 (0.14)				[59]
Food waste	24		23.2				[60]
Food waste	16				0.057	0.0944	[155]
Food waste	9-37	80-98			0.003 - 0.288	0.005 - 0.48	[155]
Food waste	9-37	75-98			0.071	0.119	[155]
Food waste	25	86			0.074	0.123	[155]
Food waste	16	87			0.057	0.095	[155]
Food waste			20			0.176	[163]
Kitchen waste				0.432			[54]
Kitchen waste				0.370-0.430			[54]
Kitchen waste				0.45			[54]
Vegetable oil			84	0.94	0.7896		[61]
Soya oil	95	90	85.5	0.8	0.684		[52]
Frying oil	95	87			0.588	0.874	[155]

Table A.9: Specification of the FW and vegetable oil - collection of the literature on cafeteria waste

Annex B

The single links to each law or ordinance do not work in the next pages.
However the whole document [122] can be asked from BiomasseSuisse [120], or if necessary from the author of the present paper.
The next pages have been copied as such from the "Manuel Qualtié Biogaz" [122].

Bases légales

Les principaux textes à prendre en compte pour une installation de biogaz, tels que lois, directives, normes et avis techniques, sont énumérés ci-dessous.

Textes	Titre et contenu
LPE, RS 814.01	Loi fédérale sur la protection de l'environnement
LAT, RS 700	Loi fédérale sur l'aménagement du territoire
OAT, RS 700.1	Ordonnance sur l'aménagement du territoire • Art. 34a : Définition des critères d'admissibilité en zone agricole pour une installation produisant de l'énergie à partir de la biomasse. Ces critères concernent les substrats entrants, les distances entre leur site de production et l'installation de biogaz, leurs valeurs énergétiques et la subordination à l'exploitation agricole.
LEne, RS 730.0	Loi sur l'énergie
OEne, RS 730.01	Ordonnance sur l'énergie • L'appendice 1.5 explique les conditions de raccordement pour les installations de biomasse, dont notamment les tarifs pour la rétribution à prix coûtant (RPC)
RPC	Directive relative à la rétribution du courant injecté à prix coûtant (RPC), Art. 7a LEne, Partie générale Directive relative à la rétribution du courant injecté à prix coûtant (RPC), Art. 7a LEne, Biomasse (appendice 1.5 OEne)
OTD, RS 814.600	Ordonnance sur le traitement des déchets (en cours de révision) • Le chapitre 6 traite des installations de compostage et de méthanisation. Toute installation traitant plus de 100 tonnes/an de déchets compostables (hors engrais de ferme) est considérée comme une installation de traitement des déchets. • Art. 43 : Exigences relatives au site et à l'aménagement de celui-ci. • Art. 44 : Exigences concernant l'exploitation et la tenue d'un registre des substrats entrants. • Art. 45 : Exigences portant sur la surveillance de l'installation.
OMoD, RS 814.610	Ordonnance sur les mouvements de déchets • Art. 2 : Définition des déchets spéciaux et autres déchets soumis à contrôle • Art. 4, 8 et 12 : Tout fournisseur de déchet a l'obligation de remettre un déchet soumis à contrôle à un centre de traitement habilité à les réceptionner. Ce dernier doit être au bénéfice d'une autorisation du canton pour la réception de ces déchets. Il doit aussi annoncer ses activités à l'OFEV.
LFE, RS 916.40	Loi sur les épizooties
OESPA, RS 916.441.22	Ordonnance concernant l'élimination des sous-produits animaux Ainsi que les explications / mises au point de l'OSAV, août 2011 • Art. 5, 6, 7 et 8 : Répartition des sous-produits animaux en 3 catégories selon leur risque sanitaire. • Art. 9 : Pas de propagation des agents pathogènes. Identification des catégories de sous-produits animaux et séparation des flux. • Art. 10 : Obligation de communication au Vétérinaire Cantonal pour toute personne éliminant des sous-produits animaux. • Art. 11 : Obligation de demander au Vétérinaire Cantonal une autorisation d'exploiter pour les installations traitant des sous-produits animaux, dont les activités sont listées à l'annexe 1.

	• Art. 16 : Séparation des activités sales et propres d'une installation (accès, stockages, exploitation, détention d'animaux). • Art. 22, 23 et 24 : Définition des méthodes d'élimination des 3 catégories de sous-produits animaux. • Annexe 1 : Liste des établissements devant avoir une autorisation d'exploiter. L'alinéa 5 spécifie le cas des installations de production d'engrais organiques et d'amendement. • Annexe 3 : Spécification des exigences que les installations de biogaz doivent satisfaire en termes de disposition des locaux (partie 11), traitement des matières et stockages (partie 23) et de coexistence avec une unité d'élevage (partie 24).
OPB, RS 814.41	Ordonnance sur la protection contre le bruit
LEaux, RS 814.20 OEaux, RS 814.201	Loi fédérale sur la protection des eaux Ordonnance sur la protection des eaux : • Art. 24 : Définition du rayon d'exploitation usuel
ORRChim, RS 814.81	Ordonnance sur la réduction des risques liés à l'utilisation de substances, de préparations et d'objets particulièrement dangereux (Ordonnance sur la réduction des risques liés aux produits chimiques) • Annexe 2.6, chapitre 2.2 : Les exigences concernant la qualité traitent des valeurs limites en polluants et substances étrangères inertes. • Annexe 2.6, chapitre 3.2.2 : L'épandage autorisé en trois ans est de 25 t au plus par hectare pour le compost et les digestats solides (matière sèche) ou de 200 m3 par hectare pour les digestats liquides, à condition que ces volumes n'excèdent pas les besoins des plantes en azote et en phosphore. Ce chapitre explique aussi qu'il est interdit d'épandre en dix ans plus de 100 t par hectare de compost ou de digestats solides comme amendements ou substrats, pour la protection des sols contre l'érosion, leur remise en culture ou la constitution artificielle de terres végétales. • Annexe 2.6, chapitre 3.3.1 : Il indique les interdictions d'épandage. • Annexe 2.6, chapitre 5 : Interdiction de l'épandage des boues de STEP.
OPD, RS 910.13	Ordonnance sur les paiements directs versés dans l'agriculture (Ordonnance sur les paiements directs) • Obligation d'utiliser HoDuFlu
OEng, RS 916.171	Ordonnance sur la mise en circulation des engrais (Ordonnance sur les engrais) • Art. 1 : Les dispositions ne s'appliquent qu'aux engrais mis en circulation. Elles ne s'appliquent pas aux engrais de ferme utilisés dans la propre exploitation ou remis directement à l'utilisateur final. • Art. 2 : Obligation d'homologation pour tout engrais mis en circulation. Il doit donc soit correspondre à la liste des engrais figurant à l'article 7, soit être au bénéfice d'une autorisation spécifique de l'OFAG. • Art. 3 : Conditions liées à l'homologation. • Art. 7 : Liste officielle des engrais. • Art. 14 à 18 : Explication de la procédure d'homologation en cas de demande d'autorisation. • Art. 19 : Toute personne souhaitant mettre en circulation un engrais correspondant à la liste des engrais doit obligatoirement l'annoncer à l'OFAG. • Art. 21a : Exigences en termes de valeurs limites de polluants, substances étrangères inertes et additifs. • Art 21b : Obligation d'une autorisation d'exploitation pour toute installation reprenant des sous-produits animaux. • Art. 23 et 24 : Prescriptions en matière d'étiquetage des produits. • Art. 24b : Tenue d'un registre des acquéreurs qui retirent plus de 5 t/a de matières sèches. Obligation du producteur de l'engrais de réaliser des analyses.

Olen, RS 916.171.1	Ordonnance du DEFR sur la mise en circulation des engrais (Ordonnance sur le Livre des engrais) • Art. 2 : Les produits des installations de méthanisation sont considérés comme annoncés si une copie de l'autorisation cantonale d'exploitation est fournie à l'OFAG. • Section 3 : Indications à spécifier sur l'étiquetage. • Annexe 1 : Liste des engrais non-soumis et soumis à annonce obligatoire. La partie 6 est spécifique aux engrais de ferme et de recyclage.
LSPro, RS 930.11	Loi sur la sécurité des produits • Art. 3 et 5 : Ne peuvent être mis en circulation que les produits présentant un risque nul ou minime pour la santé et la sécurité. Tout producteur doit pouvoir en apporter la preuve. • Art. 8 : Le producteur doit garantir la traçabilité de son produit.
ODE, RS 814.911	Ordonnance sur l'utilisation d'organismes dans l'environnement (Ordonnance sur la dissémination dans l'environnement) • Art. 6 et 12 : Toute personne mettant en circulation un produit pouvant potentiellement contenir des organismes pathogènes doit s'assurer que son produit ne présente pas de danger pour l'Homme, les animaux et l'environnement et qu'il ne porte pas atteinte à la diversité biologique ou à l'utilisation durable de ses éléments. • Art. 26 : Tout nouvel engrais mis en circulation doit être au bénéfice d'une autorisation de l'OFAG.
LAgr, RS 910.1	Loi sur l'agriculture • Art. 165f : Obligation d'utiliser l'application HoDuFlu
Ordonnance du DEFR sur l'agriculture biologique, RS 910.181	Ordonnance du DEFR sur l'agriculture biologique • Art. 1 et annexe 1 : Liste des produits phytosanitaires autorisés en agriculture biologique. • Art. 2 et annexe 2 : Liste des engrais et produits assimilés autorisés en agriculture biologique. Il y est spécifiquement fait mention des composts et digestats.
Oimpmin, RS 641.611	Ordonnance sur l'imposition des huiles minérales • Art. 19b, al. 2 : Spécification des substrats qui sont considérés comme déchets et résidus biogènes (liste positive de la DGD)
OSol, RS 814.12	Ordonnance sur les atteintes portées aux sols
Règlement G209 de la SSIGE	Règlement pour la réception technique, l'homologation et la surveillance d'installations d'injection de biogaz, G209, édition de janvier 2011 (état janvier 2014)
Directive G11 de la SSIGE	Directive pour l'odorisation du gaz
Directive G13 de la SSIGE	Directive pour l'injection de biogaz
Liste des intrants	Liste des intrants pour les installations de compostage et de méthanisation
Liste positive de la Commission de l'Inspectorat	Liste positive des matériaux de départ et des adjuvants pour la fabrication de compost et de digestat, Commission Suisse de l'inspectorat du compostage et de la méthanisation, 2006
Directive suisse 2010	Directive suisse 2010 de la branche sur la qualité du compost et du digestat
Fréquence des analyses	Fréquence des analyses de compost, de digestats et de jus de pressage en fonction de la quantité traitée ; introduction d'un système de bonus, OFAG-OFEV, 2006
Module complémentaire 8 du Suisse-Bilanz	Instructions concernant la prise en compte des produits issus de la méthanisation dans le Suisse-Bilanz, Agridea, OFAG, septembre 2013
Directive FAC Liebefeld	Mindestqualität von Kompost, 1995 (disponible uniquement en allemand)

Liste des laboratoires reconnus pour le contrôle des engrais organiques	Liste des laboratoires reconnus pour le contrôle des engrais organique de Agroscope, ART Reckenholz
Directives BioSuisse	Cahier des charges, règlements et directives pour les exploitations agricoles bio
Directives *naturemade*	Directives de certification pour l'électricité *naturemade*

Annex C

The next pages have been copied as such from the document "Installation agricoles de production de biogaz" [126]. The whole document can be consulted here: `http://www.vd.ch/fileadmin/user_upload/themes/environnement/dechets/fichiers_pdf/Check-list_Biogaz_agricole.pdf`

1. <u>Site retenu</u>

a. <u>Affectation du sol</u>

▪ Zone agricole

L'installation est **conforme à la zone** si :

- Elle est subordonnée à l'exploitation agricole et contribue à une utilisation efficace des énergies renouvelables. La subordination dépend principalement de liens fonctionnels étroits entre l'exploitation agricole et l'installation projetée, ainsi que d'une participation majoritaire de l'exploitation agricole au travail et au capital investi.
- La biomasse utilisée est en rapport étroit avec l'agriculture et avec l'exploitation.
- Au moins 50% de la biomasse utilisée provient de l'exploitation elle-même ou d'entreprises agricoles distantes de 15 km au maximum par la route. Cette partie doit représenter au moins 10% de la valeur énergétique de tous les substrats utilisés.
- Les sources des autres substrats sont situées à une distance de 50 km au maximum par la route. Des distances plus longues peuvent être autorisées à titre exceptionnel.
- L'énergie est utilisée pour la production de carburant, de combustible ou de courant par couplage chaleur-force à partir du carburant ou du combustible généré. Si elle sert principalement à la production de chaleur, celle-ci doit être destinée à des constructions et installations qui forment un ensemble avec le groupe de bâtiments centraux de l'exploitation agricole.

Si ces critères ne sont pas réunis, une **procédure de planification** est requise.

NB : L'état antérieur devra être rétabli si ces conditions ne sont plus remplies.

Bases légales : art. 16a al. 1bis et 16b al. 2 LAT ; art. 34a OAT

Instances à contacter : Municipalité, SDT Hors zone à bâtir, SAGR Constructions hors zones à bâtir

▪ Zone à bâtir, Zone spéciale

Vérifier que l'installation prévue est **conforme au règlement de la zone**.

Instances à contacter : Municipalité, SDT Hors zone à bâtir

b. Autres éléments à prendre en compte (Liste non exhaustive)

Eléments	**Services à contacter**
Protection de la nature et du paysage	SFFN – Centre de conservation de la faune et de la nature
Forêts	SFFN – Inspecteur des forêts d'arrondissement
Secteur S de protection des eaux souterraines	SESA, Eaux souterraines
Site pollué	SESA, Sols carrières et déchets
Cours d'eau	SESA, Economie hydraulique

2. Substrats utilisés

a. Général

Le projet est soumis à **Etude d'impact sur l'environnement** (EIE) si la capacité de traitement est supérieure à **5'000 tonnes de substrat par an** (substance fraîche).

Base légale : Annexe, chiffre 21.2a et 40.7, let.c OEIE

Instances à contacter : CIPE, SESA – Sols, carrières et déchets

b. Déchets

Si l'installation valorise **plus de 100 tonnes de déchets par an** :

- Elle constitue une **installation de traitement des déchets**.
- Sa **construction** est soumise à **autorisation spéciale** du Département de la sécurité et de l'environnement.
- Elle ne peut pas être aménagée à l'intérieur des zones et des périmètres de protection des eaux souterraines.
- Elle sera entourée d'une clôture, ses accès seront verrouillables.
- Elle sera soumise à surveillance de la part de l'autorité cantonale.
- Les intrants seront vérifiés et enregistrés. Les données enregistrées seront communiquées au moins une fois par an aux autorités.

Si l'installation traite plus de **1000 tonnes de déchets par an**, une **autorisation d'exploiter** sera requise.

Bases légales : art. 43 à 45 OTD; art. 22, 24 à 28 LGD; art 24b. OEng

Instance à contacter : SESA – Sols, carrières et déchets

c. Sous-produits animaux

Si l'installation prend en charge des sous-produits animaux (p.ex. restes d'aliments ou lavures, contenus de panse, sang) :

- Elle est soumise à **autorisation** du SCAV (sauf : traitement de déchets du métabolisme seuls, restes d'aliments si l'enceinte est exempte de toute unité d'élevage).
- Le traitement doit garantir la **qualité hygiénique** du procédé et de ses produits.

- L’installation sera construite et équipée de telle manière que les activités « **souillées** » soient **séparées** des activités « **propres** » et que la contamination des sous-produits animaux transformés soit impossible.
- Des règles techniques précisées dans les annexes de l’OESPA seront à respecter en particulier quant à la conception du site, l’équipement des locaux, le nettoyage et la désinfection, l’exploitation de l’installation et les méthodes de transformation des sous-produits animaux à appliquer pour garantir leur innocuité du point de vue de l’hygiène.

Les cantons surveillent l’élimination des sous-produits animaux. Ils contrôlent au moins une fois par an les usines ou les installations.

Bases légales : en particulier art. 9, 24, 34, chiffres 23 de l’annexe 2, 3 de l’annexe 3 et, 34 de l’annexe 4 OESPA

Instance à contacter : SCAV - Vétérinaire cantonal

d. Déchets soumis à contrôle

Certains déchets sont désignés comme « soumis à contrôle » par la législation fédérale. Leur prise en charge est soumise à **autorisation cantonale (SESA)**.

Ceci concerne plus particulièrement :

- Les **huiles** et **matières grasses alimentaires** collectées séparément (code OMoD 20 01 25) ou provenant de séparateurs de graisses (code OMoD 19 08 09). Les quantités éliminées sont à déclarer une fois par an à l’autorité de contrôle. La prise en charges de matières grasses non alimentaires et d’huiles provenant de postes de collecte publics est exclue ici.
- La **glycérine** résultant de la fabrication de biodiesel contient des impuretés telles que méthanol et potasse caustique. Elle peut donc présenter des dangers en raison de son alcalinité et d’un point-éclair bas. Des précautions particulières sont requises pour son transport, son stockage et son traitement. Elle constitue un **déchet spécial** (code OMoD 19 02 08). Chaque mouvement doit être accompagné d’un **document de suivi** et faire l’objet d’une déclaration à l’autorité cantonale une fois par trimestre.

Bases légales : art. 2, 8, 11 à 13 et annexe 1 OMoD, LMod

Instance à contacter : SESA – Assainissement industriel

3. Maîtrise des odeurs

La prise en charge et le traitement de déchets organiques fermentescibles sont susceptibles de générer des odeurs incommodantes. Or, selon les principes qui régissent l'OPair, le voisinage doit être préservé d'immissions d'odeurs excessives. Il y aura dès lors lieu de prendre à titre préventif toute mesure utile qui vise à limiter les émissions olfactives et de veiller en permanence à leur application. Ces mesures concernent en particulier la gestion des produits entrants, celle des produits issus du procédé de méthanisation, le stockage temporaire des produits et, cas échéant, l’entretien des ouvrages de traitement des rejets gazeux (bio-filtre p.ex.).

En cas de plaintes fondées, des mesures complémentaires pourront être prescrites.

Bases légales : art.7 al.3 et art.14 LPE ; art.27 al.1 et art.2 al.5 OPair

Instance à contacter : SEVEN – Protection de l’air

4. **Produits du traitement (« Digestats »)**

a. Caractérisation

- **Substrats d'origine agricole > 80% du total des intrants :**

  Le produit (« digestat ») est défini comme un « **engrais de ferme** ».

- **Substrats d'origine agricole < 80% du total des intrants :**

  Le produit (« digestat ») est défini comme un « **engrais de recyclage** ».

Base légale : art. 5, al.2, let. a et b, chiffre 2 OEng

b. Dispositions s'appliquant à tous les digestats

Les digestats doivent être homologués et annoncés à l'OFAG pour pouvoir être mis en circulation.

La teneur des digestats en **polluants** et en **éléments nutritifs** doit être **analysée** au moins une fois par an. Les résultats des analyses sont à mettre sans délai à la disposition des autorités fédérales et cantonales. La **fréquence** des analyses dépend de la quantité prise en charge.

La teneur en métaux-lourds des digestats doit respecter des **valeurs-limites**.

Un **bulletin de livraison** détaillant la composition des digestats est à remettre aux utilisateurs, accompagné d'un **mode d'emploi** précisant notamment la quantité autorisée pour des besoins moyens.

Les **acquéreurs** de digestat retirant plus de 5 tonnes de matière sèche par an doivent être enregistrés. Les données recueillies sont à tenir à la disposition des autorités.

Bases légales : art. 44, al. 1, let.c OTD; art. 2, 19, 21a, al. 1, 24 et 24b OEng ; Annexe 2.6, chiffres 2.2.1, al. 1 ORRChim

Autres :

- *Recommandation sur la fréquence des analyses des composts, digestats et jus de pressage en fonction de la quantité traitée – OFAG et OFEV 2006*
- *Caractéristiques de qualité des composts et des digestats provenant du traitement des déchets organiques – Directive ASIC 2001*

Instance à contacter : SESA – Sols, carrières et déchets

c. Dispositions particulières s'appliquant aux engrais de ferme

La remise du digestat fait l'objet de **contrats** avec les preneurs, soumis à l'autorisation de l'autorité cantonale.

Un **registre** indiquant le nom des preneurs, la quantité remise et la date de la remise est tenu et présenté à l'autorité cantonale sur sa demande.

Une homologation n'est pas requise si le digestat est cédé directement par l'exploitation pratiquant la garde d'animaux de rente à l'utilisateur final.

Bases légales : art. 2, al.1 OEng; art. 14, al. 4 et 5 LEaux; art. 26 et 27 OEaux

Instance à contacter : SESA – Assainissement urbain et rural

d. **Dispositions particulières s'appliquant aux engrais de recyclage**

En plus des valeurs limites concernant la concentration en métaux-lourds, des teneurs indicatives sur la présence de certains **micropolluants organiques**, ainsi que des exigences concernant celle de **corps étrangers** (pierres, métaux, verre, plastiques) s'appliquent aux digestats remis comme engrais de recyclage.

Les épandages sont limités à 25 tonnes de matière sèche par hectare sur 3 ans pour les digestats solides et à 200 m3 pour les digestats liquides, à condition que ces quantités n'excèdent pas les besoins des plantes en azote et en phosphore.

Cette limite est portée à 100 tonnes par hectare sur une période de 10 ans pour les digestats solides utilisés comme amendements ou substrats, pour la protection des sols contre l'érosion, leur remise en culture ou la constitution artificielle de terre végétale.

Bases légales : Annexe 2.6, chiffres 2.2.1, al. 2 et 3, 2.3.1 à 2.3.4, 3.2.2 ORRChim

Instance à contacter : SESA – Sols, carrières et déchets

e. **Dispositions particulières s'appliquant en cas de prise en charge de sang dans l'installation**

Lorsque du sang est utilisé pour la production de biogaz, l'utilisation du digestat comme engrais demande une **autorisation** particulière **de l'OFAG**.

De plus, avant d'être valorisé comme constituant d'engrais, le sang doit être stérilisé sous pression.

Références :

BiomasseEnergie, Le centre d'information de Suisse-Energie :

http://www.biomassenergie.ch/Commentproduire/Agriculture/Biogaz/tabid/326/language/fr-CH/Default.aspx

Agridea, Développement de l'agriculture et de l'espace rural : Energies renouvelables, Classeur Octobre 2008

http://www.agridea-lausanne.ch/scripts/publications/publications.php

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